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TITLE: IMPROVED FIELD PERFORMANCE FOR
REVERSE OSMOSIS SYSTEMS

AUTHOR: T. A. Kuepper

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METRIC CONVERSION FACTORS

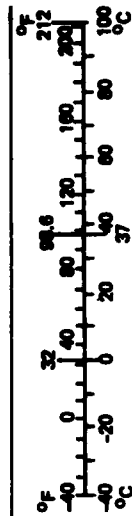### Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.8	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	35	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

°F   -40   0   32   40   80   98.6   120   160   200 212 °F
°C   -40   -20   0   20   37   40   60   80   100 °C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The report describes two test programs: the first one involved the physical cleaning of reverse osmosis (RO) membranes by means of flow surging and ultrasonic cavitation. The objective was to clean RO membranes in situ without using chemical additives. It was shown that ultrasonic cleaning is an effective method for removing ferric oxide, calcium carbonate/ sulfate scale, and bentonite clay deposits from individual pieces of RO membranes. However, ultrasonic cavitation was not effective when applied to RO membranes in a spiral-wound

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20. Continued

configuration. Flow surging proved to be an effective method for cleaning spiral-wound RO modules in the preliminary test program conducted. A second test program involved the evaluation of a tubular fabric filter which has the potential of replacing conventional mixed media filters with substantial weight and filter housing area savings. During the test program the filter removed over half of the turbidity of the feedwater used without any chemical additives and could be cleaned intermittently by backwashing.

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INTRODUCTION

Reverse osmosis (RO) is now a commercially feasible, widely used technology. In spite of the commercialization of RO technology however, there exists a continuing need for process improvement. As an example, water production rates are relatively low for RO membranes - on the order of 10 to 20 gal/ft^2 of membrane surface/24-hour day using a <u>clean</u> membrane and <u>clean</u> water source. In order to compensate for this low production rate, the most popular commercial RO modules are manufactured with relatively high packing densities. The spiral module used within the Army and Marine Corps 600 gph Reverse Osmosis Water Purification Unit (ROWPU) is one of the high packing-density configurations. As the packing density increases within the RO module, the ability to clean the entire membrane surface decreases. It is therefore more important to be aware of membrane fouling limitations and cleaning requirements when using the spiral-wound configuration than for other less densely packed RO modules.

Another characteristic of the RO process is the need for high pressures to drive the purified water through the membrane. Typical pressures for operating on brackish water or freshwater is 400 to 600 psi while, on seawater, is about 1,000 psi. A proportionately high energy cost is associated along with these high pressures. Although not as great as the distillation process, the energy expenditure for RO is a limiting factor for portable mobile applications due to the size and weight of associated pumps, motors, and electric generators.

In order to accommodate modest water production rates and moderately high energy expenditures, RO systems must be designed to keep the membrane as clean as possible for as long as possible. The conventional way of keeping membranes clean is either of two methods: the first is to administer chemicals to periodically clean adhering contaminants from the membrane or to add chemicals to the feedwater to keep potential contaminants from precipitating within the RO module; the second is to pretreat the feedwater to remove those contaminants known to foul RO membranes. For fixed installations, the above two methods are acceptable and used routinely. For the portable, mobile RO unit, chemical additives and pretreatment hardware are not as acceptable as for fixed installations and in some cases can prohibit true mobility due to chemical logistic trains and size/weight of pretreatment equipment.

Chemicals are often administered continuously during RO operation to keep waterborne materials from precipitating within the RO module and causing eventual plugging of the membrane. In addition, other chemical additives are used periodically (perhaps once or twice per day) to clean and restore the membrane's water production rate. For the mobile/portable application, supplying the chemicals in field locations can be burdensome at the least and can be a limiting constraint if resupply is not consistent and reliable.

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Conventional pretreatment equipment has been optimized to operate in fixed locations and has also been developed to minimize energy and personnel interactions. Although land area requirements are an important aspect of pretreatment system design, few pretreatment systems have been designed to operate within minimum space. Consequently, most pretreatment systems are bulky and heavy and have little application in portable operation.

Sand or mixed-media filters are good examples. They are very effective for RO pretreatment while requiring modest land requirements (3 to 6 gpm/ft^2) in addition to a number of ancillary facilities, including pumps and backwash storage tanks. The filter media usually has a specific gravity in excess of 1.5, which means the sand filters are quite heavy. For example, a typical sand or mixed-media filter contains a 30-inch depth of filter media or about 800 pounds of sand for a 30-in.-diam filter housing. This weight is for the sand only and does not include the filter housing or any of the ancillary hardware components.

Besides the bulk of pretreatment equipment and the chemical resupply necessary, another limiting constraint is the necessity of replacing filter media when cartridge-type filters are used within the prefiltration system. Cartridge filter designs employ disposable "throw-away" media which must be replaced when fouled. The logistic burden potential for this type of filter can be operationally prohibitive under highly contaminated feedwater conditions.

The effort reported here was directed toward reducing the weight and size of the multimedia filter and the need for frequent media replacement of the cartridge filter within the existing prefiltration system of the 600 gph ROWPU. This was to be accomplished by developing a lightweight modular filter capable of replacing the existing sand and cartridge filters in the ROWPU. In addition, this work effort was also directed toward increasing the water production rate through the RO membrane between programmed chemical cleaning cycles. A physical cleaning technique was to be used without any additional logistic resupply requirement.

Improvements anticipated include increasing the ROWPU water production rate while maximizing RO membrane life by reducing membrane interaction with feedwater contaminants. Additional improvements include decreasing cartridge filter replacement requirements and allowing the ROWPU to operate on all feedwater sources, including highly contaminated brackish river and lake water sources, seawater, and laundry/shower wastewater. The added ability for the ROWPU to operate on laundry/shower wastewaters will enable military forces to recycle water in the combat base environment, thus reducing water production requirements.

BACKGROUND

Reverse Osmosis Process

The reverse osmosis process is a pressure-driven membrane separation process which employs high pressure to overcome the water feedsource's osmotic pressure caused by soluble organic and inorganic substances. Water is forced through the membrane which is generally impermeable to

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organic chemicals and inorganic ions, thus producing a purified water-stream. Four basic RO module configurations are in commercial use: tubular, hollow fiber, plate and frame, and spiral wound. Currently, spiral-wound modules are most widely marketed while plate and frame systems are the least marketed. The two major classes of RO application are desalination and the treatment of industrial wastewaters. For desalination, compact spiral-wound or hollow-fiber modules are usually preferred for economic reasons, and work well since feed streams in many parts of the world are relatively clean. With severely contaminated natural waters and wastewaters, hollow-fiber and spiral-wound modules are often ruled out because of their inherent tendency to foul and plug. These modules usually require substantial pretreatment to ensure acceptable fouling rates under rigorous operating conditions. Although tubular modules are the most trouble free they are also considerably more expensive and require more working space than the other configurations.

As previously mentioned, the spiral-wound configuration, illustrated in Figure 1, is the module type employed within the 600 gph ROWPU. Figure 1 also shows the specific functional components of a module. The flat sheet components are rolled around a central tube in which the purified water (or permeate) is collected. The feed channel spacer is placed between two layers of membrane so that the rejection or barrier surface of the membrane faces the spacer netting. The feed flow enters the rolled-up module in a direction parallel to the permeate tube. The hydrostatic pressure produced by pumping action forces water through the membrane and into the permeate collection material which leads to the permeate collection tube. The permeate tube is perforated to allow passage of purified water into the tube.

Military RO Hardware

The development of the RO process into military water purification equipment has provided a solution to the problem of procuring potable water from sources available in a combat field environment. The ROWPU is capable of treating freshwater, brackish water, and seawater. In addition, the capability to treat waters contaminated with nuclear, biological, and chemical warfare agents is to be provided by the RO equipment used in conjunction with auxiliary ion exchange and carbon adsorption units.

The ROWPU is capable of producing about 10 gpm (600 gph) of product water from freshwater sources and 6.6 gpm (400 gph) of product water from seawater (temperature corrected to 70°F) (Ref 1). The rate of water production in the ROWPU depends upon the operating pressure, normally 350 to 550 psig for freshwater and 750 to 950 psig for seawater. At the same pressure, temperature affects the rate of flow: cold water decreases the flow while warmer water increases flow. However, the maximum operating temperature for the ROWPU unit's feedwater is about 120°F. Sustained water temperatures above this figure may damage the membranes within the RO modules.

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Chemical Requirements

Four chemicals are used to maintain the ROWPU rated production levels. These chemicals are polyelectrolyte (polymer), sodium hexametaphosphate (Sodium Hex), calcium hypochlorite (chlorine), and citric acid. Polymer is continuously fed into the feedwater in order to agglomerate small particles into larger particles that can be removed by the pretreatment units prior to use of the RO modules. Sodium Hex is fed into the feedwater in order to prevent calcium scaling. Chlorine is injected in the RO product waterline and is used as a disinfectant to inhibit bacteria and other microorganism growth in the product water storage and distribution system. Chlorine is introduced after the RO equipment (rather than before) because the membranes used in the ROWPU cannot tolerate disinfecting concentrations of chlorine. Citric acid is used periodically to clean the RO membranes from fouling material by feeding citric acid into the filtered water intake to the RO modules. Used periodically, the citric acid solubilizes fouling materials such as metal hydroxides and sparingly soluble salts. A rather complete list of foulants and corresponding chemical cleaning agents is presented in Table 1.

Using the aforementioned chemical additives is the conventional method of cleaning RO membranes in situ. They work quite well and possess only two disadvantages to universal application. Chemicals require (1) a logistic train to transport and handle the materials in bulk form and (2) trained personnel to administer the chemicals in proper concentrations and suitable injection points.

These disadvantages generally do not adversely impact RO systems located at fixed installations. Although reliability of chemical suppliers and employees to maintain chemical additive systems is a variable which all managers of water purification equipment must live with, these disadvantages take on significant importance when a RO unit is to be used in relatively remote locations throughout the world. Depending upon the feedwater source and its inherent fouling characteristics, interruption of chemical additions for whatever reason can severely restrict RO equipment water production rates.

Previous Fouling Studies

Previous studies have been performed to investigate the nature of fouling materials on RO membranes, mechanisms of foulant buildup, and interrelationships between fouling and operating parameters (Ref 2, 3, 4, and 5). Approaches have included examination of fouled materials by chemical and physical means, as well as studies of chemical interactions between membranes and chemically active foulant solutes. Although chemical interactions do occur between membranes and foulants, they are usually not of the type which involve rupture and formation of chemical bonds. Therefore, physical cleaning methods have been found to be effective for many applications.

A reverse osmosis physical cleaning technique able to minimize the chemical cleaning additions required to maintain realistic water production rates has tremendous application for mobile or remote location designated equipment.

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Previous Physical Cleaning Investigation

Work had been conducted at NCEL prior to the current Marine Corps project in which a variety of physical cleaning methods that could be used to clean RO membranes were investigated. Since it was desired to give the physical cleaning techniques the best opportunity possible, a tubular RO configuration was chosen as being most easily adaptable for test and evaluation. The physical cleaning techniques chosen for investigation included: air insertion (surging and continuous), flow surging and depressurization, and ultrasonic cavitation as well as combinations of the different methods. Figure 2 shows the hardware configurations used for the ultrasonic equipment; Figure 3 shows test results of the evaluation of flow surging and ultrasonic cavitation, the most successful methods tested (Ref 6). As can be seen in Figure 3, whenever the physical cleaning technique was implemented, the water production rate, or permeate flux, increased in the two RO modules.

Testing began with a chemical cleaning to differentiate its results from that of previous tests. During the day-long evaluation, the permeate flux decline was modest, maintaining a high level of water production and not requiring chemical cleaning at the end of the day. This type of result is exactly what was desired for the ROWPU modules although it was realized that the ROWPU spiral wound configuration was substantially different from the previously tested tubular configuration. This report is the continuation of this initial reverse osmosis physical cleaning investigation.

Feedwater Pretreatment

Pretreating the feedwater before insertion into the RO modules is another method for reducing the water production rate decline. This is a preventive maintenance procedure where known foulants are either removed or rendered innocuous before they can contact the RO membranes. In previous work, contaminants potentially harmful to RO membranes were identified and categorized for seawater, brackish water, and laundry/shower wastewater (Ref 7); these data are presented in Tables 2, 3, and 4, respectively, and a summary shown in Table 5. In addition, Table 6 shows seawater composition for a variety of worldwide locations identified during previous studies.

Previous Pretreatment Investigation

The initial objective of the pretreatment process investigation was identification of hardware or technology that could augment the existing pretreatment equipment of the ROWPU. The intention was to identify equipment that could be used upstream of the ROWPU's pretreatment system for those locations where additional treatment of the influent waterstream was necessary. In addition to natural water applications, it was recognized that the existing ROWPU pretreatment system was not adequate to operate in a recycling mode using laundry/shower wastewater as the feed source. Therefore, it w⁻ desirab¹ that the new processing equipment also treat laundry/shower⸳ tev ⸳r, allowing wastewater to be handled by the ROWPU pretreatment ⸳ ipment.

Twenty candidate pretreatment processes were evaluated on paper in relation to the aforementioned source-water contaminants (see Table 7). From this list, three combinations of equipment or systems were chosen for consideration, as shown in Figure 4; only system C has the potential for lightweight, compact packaging (Ref 8).

The roughing filters identified in systems A and B consist of coarse-media depth filters identical in principle to the multimedia filter presently used in the ROWPU pretreatment system. The difference between the filters is that the roughing filter media has relatively large particle sizes to remove larger contaminants than a conventional multimedia filter would remove. The two depth filters, therefore, if used together, would complement each other.

System C is identified as using what is termed a cross-flow filter. Unlike the previously discussed depth filter, a cross-flow unit is a surface filter utilizing only its surface to separate water and contaminants. Unlike the depth filter which can use its media volume to perform the required separation, a surface filter must rely solely on the square footage of its surface to provide adequate separation performance. Although surface filters have much greater surface area requirements than depth filters, the surface filter media can be (and is) lightweight and is designed in relatively high packing density configurations to maximize surface area. The inherent operational advantage of the surface filter compared to the depth filter design is that the surface filter can be subjected intermittently or continually to rather simple physical cleaning techniques in order to clean the filter surface. The cross-flow technique employs contaminated water flow parallel to (or tangential to) the surface of the filter. Purified water is driven via modest pressures (<50 psig) through the cross-flow filter in the same manner as in all surface filters. That is, purified water travels approximately perpendicular to the surface of the filter. The cross flow design, however, allows the bulk of the water flow (typically 50% to 90% of the influent) to aid in keeping the surface of the filter clean by continually sweeping past the filter surface with water in the turbulent flow regime.

Concurrent with the pretreatment process evaluation, researchers from NCEL were developing a surface oil coalescer to remove oil and dirt from a contaminated watersource. The media chosen for this application were lightweight cloth fabric tubes. The objective of the design work was development of a combination surface coalescer and filter that would perform as well as a depth coalescer and yet be easily cleaned. This work culminated in the issuance of a patent for the unique coalescer and filter design (Ref 9).

The cross-flow filter configuration identified in the pretreatment process evaluation was readily adaptable to the newly patented surface coalescer/filter; therefore the two designs were incorporated into a modified configuration named the Tubular Fabric Filter, or TF^2, reported herein.

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PHYSICAL CLEANING

The spiral-wound RO configuration shown in Figure 1 was used during the physical cleaning investigation. When ultrasonic cavitation was evaluated, a cylindrical ultrasonic transducer configuration (Figure 5) was employed. All testing was conducted by Walden Division of Abcor, Inc. at their Wilmington, Mass. facility (Ref 10).

Tests were conducted using synthetic laundry/shower wastewater, samples of actual seawater collected from a location on the Atlantic coast near Boston (Beverly Beach, Mass.), solutions containing scale formers (calcium carbonate and calcium sulfate), and suspensions of ferric oxide and bentonite clay. The calcium salt solutions were used because they simulated a concentrated batch of seawater. Bentonite coagulating aid was used because it has shown that it severely fouls RO modules when there is carryover in the effluent from clarifier pretreatment; ferric oxide was used because it is a principal component of the ever-present foulant - rust. The combination of the latter two foulants was particularly useful for measuring cleaning efficiency on the basis of flux recovery, area cleaned, and weight reductions. RO system performance in treating these process fluids was monitored by measuring flow rates (feed, permeate, and concentrate) and salt concentration. Calculations were made of permeate flux measured in gallon per square foot per day (gfd), percentage salt rejection, and product recovery.

Several of the tests with the fouling feeds were batch-concentration tests (where product water was not returned to the feed tank) rather than total-recycle tests because, generally speaking, concentrating contaminants in the fee results in more rapid fouling of membranes. This is especially true in the case of scale-forming foulants, as higher concentrations precipitate the sparingly soluble salts, which are the principal components of scale. High pressure tests were performed to determine whether cavitation can be achieved at the standard operating pressure (600 psig) or whether depressurization to 0 psig was required. It should be noted that when 0 psig pressure is shown with a corresponding water flow through the test module, actual driving pressure is approximately 20-30 psig. Tests were also performed to determine whether or not cavitation is required for cleaning. For all tests using fouling feed, chemical cleaning of both modules was conducted before each test. If flux decline for the module not ultrasonically cleaned was excessive (greater than 50%), then chemical cleaning during the course of testing was performed. The chemical cleaners recommended by the membrane manufacturer (e.g., oxidizing agents such as citric acid) were used. At the completion of testing, the ultrasonically cleaned modules were cut apart and from the appearance of the membrane it was determined whether the entire length or depth of the spiral-wound modules was effectively cleaned. From inspections of this kind, recommendations were to be made for optimal configurations of the RO system and the ultrasonic cleaning device and for optimal operating parameters.

Synthetic Laundry/Shower Wastewater

Ultrasonic Cleaning with Flow Surges. The initial investigation into the impact of ultrasonic cleaning on a spiral-wound, RO module included attempts to effect cleaning at voltages from 10 to 60 volts (1.3 to 46.8 watts) for periods of 1 to 5 minutes. It should be noted that power values have been estimated from a standard plot of power versus voltage squared, which is derived assuming the slope (inverse of impedance, 0.013 S) is constant. For the data given here the relationship between power (P) and voltage (V) is $P = 0.013\ V^2$. Power data provided in parentheses throughout the report were obtained in this manner. The results of this series of tests are presented in Figure 6. It appeared that the ultrasonic device significantly affected the flux upon first viewing this set of data. The peaks occurring at 6.5, 9, and 10.5 hours suggest that operation of the ultrasonic device led to an enhanced increase in flux. To the contrary, the activation of ultrasonics at 1, 4.5, and 8.5 hours supports the notion that flux is enhanced without the ultrasonic device. Careful examination revealed that whenever the normal operating conditions were altered, the flux was affected. The "flow surges" (FS) caused by shutting off the RO system during ultrasonic operation and then turning the system on again appear to have a significant impact on the flux. Therefore, little can be concluded from the ultrasonic performance data; however, because of the response of the control module, it is safe to state that severe changes in the flowrate (flow surges) tend to enhance the flux, most likely by sweeping away some of the foulant layer.

In Figure 7, a combination of ultrasonics and various levels of flow surging was attempted; however, again no significant difference was discerned between the ultrasonic module and the control. As in all of the tests conducted, the experimental and control modules were operated under similar conditions except that the control module was not exposed to ultrasonic energy.

Throughout most of the tests following, a special effort was made to reduce the impact that operating conditions (i.e., changes in flow rate) had upon flux values in order to document the effect of ultrasonic cavitation alone.

Ultrasonic Cleaning Without Flow Surges. In Figure 8, the results of attempted ultrasonic cleanings at 80 volts (83.2 watts) are represented. The operating conditions employed for the RO system during activation of the ultrasonic device were the same as those employed throughout normal operation (i.e., 500 psi) without depressurization. This procedure was aimed at minimizing the effect of operational variations on flux values for the data obtained in Figures 8 and 9.

At 83.2 watts (or 80 volts in Figure 8), and less significantly at 130 watts (or 100 volts in Figure 9), operation of the ultrasonic device increased the flux. It was noted that in each instance of ultrasonic cleaning, the permeate produced by the ultrasonic module was warmer than the permeate produced by the control module. This is consistent with experimental observations of heat generation from the collapse of cavitational bubbles. In addition to the enhanced water production due to ultrasonic cleaning, the warmer permeate would have a lower viscosity;

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and, since less viscous fluids tend to pass through the membrane more rapidly, the flux value would be increased. Extensive experiments aimed at a more conclusive determination of the impact of ultrasonic exposure on fresh spiral-wound RO modules were planned.

Ultrasonic cleaning was again attempted when the RO system was not depressurized, and the results are given in Figure 10. These data contrast the results in Figures 8 and 9 and suggest that system depressurization is required for effective cleaning.

Fresh RO modules were employed for the continuation of experiments to discern the impact of ultrasonics on flux values over treatment periods ranging from 8 to 20 hours. The data represented in Figures 11 and 12 were obtained by following a single approach to ultrasonic operation. During these tests, the RO system was depressurized prior to activation of the ultrasonic apparatus. The temperature of the process fluid and its flowrate through the modules remained essentially constant during normal operation as well as during ultrasonic activation. This constant temperature suggests that when the RO module was depressurized during ultrasonic cleaning, turbulence rather than heat was the primary product of cavitation.

The experiments represented in Figure 11 were performed using an approach aimed at maximizing the flux through closely spaced, intermittent ultrasonic operation over longer periods of system operation that had been used previously. It was hypothesized that a preventive approach to fouling might be more effective than a remedial approach entailing "spot" cleaning conducted only after severe flux decline. From these data it appears that ultrasonics was only moderately effective in dealing with this particular foulant. However, it was clearly demonstrated that the foulant layer that formed on the membrane was easily removed by simple flow surges.

Figure 12 is included in this report to illustrate the confusing effect that variations in pressure have upon the flux levels. These data imply that a degree of cleaning can be accomplished by merely depressurizing the RO system without flow surges since flow rates were held constant throughout the duration of this test.

Threshold for Module Damage. An attempt to clean ultrasonically at 125 volts (203 watts) resulted in membrane failure. The operational life-span of the two modules is plotted in Figure 13 in terms of rejection versus time. The high rejection values recorded throughout the 52 hours of operation during which the data in Figures 6 through 10 were recorded, indicate that the two modules were functionally sound. Upon exposure to ultrasonic energy at 125 volts while the RO module was constantly subjected to 600 psig, the ultrasonically cleaned module failed to exhibit a rejection above 90%. In fact, following this test, the rejection percentage declined to zero, indicating that the process fluid was passing through the membrane untreated and that the integrity of the membrane had been altered.

A blue dye of sufficiently large molecular size that would not normally pass through the membrane was circulated through the module in order to highlight the damaged areas. The membrane backing in damaged areas was thus stained blue, while the undamaged sections remained white. Dissection of the module revealed a 1-in.-long area on one side of the

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permeate tube where the high-temperature PVC material had been melted by the ultrasonic energy. Blue dye had passed through the membrane, staining the backing in areas located close to the melted section. Flat cell tests of membrane samples excised from the module at intervals from the exterior to interior spiral layers indicated that the damage was localized in one area near the permeate tube. These three bits of evidence support the hypothesis that the focusing of energy in the longitudinal and circular center of the transducer overcame the disseminating influence of the membrane, feed channel spacer and permeate collection material. Moreover, heat loss from this focal point was prevented by the insulating action of the spiral layers. The heat generated as a result of the collapse of cavitational bubbles raised the temperature to the melting point of the CPVC tubing. In the area where the heat damaged the tube, it also damaged the membrane. This theory was substantiated when an attempt to melt a CPVC permeate tube having no membrane, Tricot, or Vexar covering failed, even when 150 volts (292.5 watts) was applied to the transducer.

Chemical Cleaning. Chemical cleaning of the RO modules was performed in order to establish productivity baselines. The original fluxes were 8.4 and 13.2 gfd for modules 2 and 3, respectively. These declined to 3.7 and 4.2 gfd over the course of operation using the fouling feed. Citric acid cleaning showed little effect as the flux values only increased to 4.8 and 4.6 gfd. Circulation of a detergent similar to "Biz" (an enzyme-activated detergent solution) cleaned the modules, raising the fluxes to 6.3 and 6.6 gfd. These were considered the maximum values for the two modules because a certain degree of fouling is irreversible and is dependent upon the essential characteristics and interaction of the membrane and foulant during the course of a typical operating period.

Actual Seawater Tests

Ultrasonic Cleaning Tests. A set of fresh RO modules were fabricated for treatment of actual seawater. The data presented in Figures 14 and 15 were obtained again by adhering to a single approach to ultrasonic operation. During these tests, the RO system was depressurized prior to activation of the ultrasonic apparatus. The temperature of the process fluid remained constant during each operational period while the flow-rate through the modules was altered only in the instance labeled "flow surge" in Figure 15.

The experiments represented in Figures 14 and 15 were performed with an approach aimed at minimizing fouling and flux decline through ultrasonic operation at intervals spanning a 6-hour period. The data show no significant difference between modules no. 6 and 1 (ultrasonic and control, respectively). Figure 14 illustrates again that variations in pressure have a positive effect upon flux levels. The data imply that a degree of cleaning can be accomplished by depressurizing the RO system, even without flow surges. Throughout the test periods monitored in Figures 14 and 15, no significant differences can be discerned between the ultrasonically activated module and the control. During each 6-hour period the flux declined roughly 1 gfd for both modules.

Chemical Cleaning. The ultrasonic and control modules were chemically cleaned with a 2.0% (by weight) citric acid and a 0.5% (by weight) solution of Biz detergent before and after the data in Figures 14 and 15 were taken.

Threshold for Module Damage. An investigation into the potentially detrimental effect of ultrasonic exposure on RO modules was initiated in order to better define a maximum voltage at which the ultrasonic device could be operated without destroying membrane function. Module no. 2, a module previously used as the control for experiments with synthetic laundry/shower wastewater, was exposed to potentials of 100, 120, and 150 volts. Figure 16 shows the results in terms of flux and rejection percentage versus time. The conditions for this experiment were almost identical to those under which the permeate tube of a previous module was melted. The variable in this case was the pressure under which the module was exposed to ultrasonics: 0 psig rather than the 600 psig used previously. The flux increased with repeated exposure to high voltages, and the rejection percentage reciprocally declined, indicating that damaged areas of membrane allowed salt to pass through. Even so, the permeate tube was not harmed by the ultrasonic device at higher voltages and atmospheric pressure. This supports the hypothesis that the energy input to the module under high pressure resulted primarily in heat generation which melted the permeate tube. At atmospheric pressure the energy was dissipated in forms related to the scattering of cavitation bubbles causing localized pressure and heat throughout the process fluid.

Ferric Oxide Suspension Tests

Module no. 2, formerly used as the control in experiments with synthetic laundry/shower wastewater fouling and for determination of the threshold voltage correlated to ultrasonic module damage, was employed to treat a suspension of ferric oxide in RO permeate. The impact of ultrasonics on the removal of a clearly visible layer of ferric oxide was measured in several ways. The distinct reddish-brown color of the ferric oxide made it possible to calculate cleaning efficiency visually by area cleaned. In some instances, significant flux increases occurred as a result of ultrasonic cleaning.

Modules no. 1 and 6 were employed to treat a suspension of 100 grams ferric oxide in 20 liters of RO permeate (5 g/l). As shown in Figure 17, the modules were contaminated with this feed for 50 hours of continuous operation at the end of which several ultrasonic applications showed minimal influence on flux. Module no. 6 was dissected and examined for visible effects of ultrasonic exposure. It was concluded that ultrasonics was ineffective in cleaning the RO membrane during this test. Samples of membrane large enough to fit on the flat-cell test system were excised from module no. 6. Flux values were obtained for the highly contaminated membrane discs before and after ultrasonic cleaning. Figure 18, a graph of some of the data in Table 8, shows the impact of ultrasonic cleaning on individual samples of membrane. It is clear that those exposed to ultrasonics showed enhanced fluxes. Visual inspections of the same membrane samples used for Table 8 indicated a close correlation between flux enhancement and visual removal of the reddish-brown

color of the ferric oxide foulant. Figure 19 shows the results of the visual inspections performed on the membrane samples. Thus, Figure 19 shows the percentage of area cleaned as it was measured visually, while Figure 18 corresponds with these data by providing evidence of flux enhancement due to ultrasonic application.

Calcium Scale Tests

Tests similar to the ferric oxide series were executed using a feed consisting of calcium carbonate and calcium sulfate in Wilmington, Mass. tap water. Flux data for spiral modules tested for 75 hours with this solution are presented in Figure 20. As with the other fouling feeds, it was found that the application of ultrasonics to the spiral-wound module caused a discernible flux recovery that was approximately equal to the flux increase caused by merely depressurizing the control module. Individual samples of membranes excised from that module were cleaned by ultrasonics, visually inspected and the results are shown in Table 9 and Figure 21, where it is calculated that ultrasonics cleaned 31% of the membrane area.

Bentonite Clay Tests

The fifth type of foulant tested, bentonite coagulating aid, is representative of the general category of aluminum silicate colloid (clay) foulants. The use of clay was the most successful of the foulants tested because of its substantial impact on the flux as well as its visible appearance, discernible mass, and greater adherence to the membrane surface.

A suspension of bentonite coagulating aid (20 grams/16 liters H_2O) was prepared for treatment by spiral-wound module no. 4. Over an 11-hour fouling period the flux declined 30%, a loss of productivity which three consecutive ultrasonic activations at 125 volts for 2 minutes failed to recover.

Fouling of flat-cell samples of membrane with a similar clay suspension was continued to determine the efficiency of the ultrasonic device in cleaning membrane fouled by clay. A 0.06-inch foulant layer composed primarily of clay, with some residual iron oxide, caused an average flux decline of 46%. Cleaning efficiency determined by visual inspection is detailed in Table 10 while Table 11 data show the flux recoveries due to ultrasonic activation.

The cleaning efficiencies calculated from visual area measurements and calculated from initial, precleaning (fouled), and postcleaning flux values are not compatible because visible membrane damage was noted on all three ultrasonically cleaned samples. Clay deposition resulted in a thicker foulant layer and displayed a greater tenacity for the membrane; it consequently required potentials of 100 to 150 volts to facilitate removal. The order of magnitude was two to three times greater than the voltage required to remove iron oxide and calcium salts. Because of the high voltages used, postcleaning fluxes in all three samples were higher than initial flux values (before adding foulant) because the membrane was sufficiently damaged, allowing a high percentage of the product water to bypass the membrane.

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Ultrasonic Cleaning of Stacks of RO Module Materials

In an effort to explain the excellent cleaning obtained for single membrane disks and the poor cleaning obtained for spiral-wound membranes, stacks of membrane, feed channel spacer material (Vexar), and permeate carrier (Tricot) were tested. Figure 22 shows the basic stack. Tests were performed using groups of several 4-cm-diam pieces of membrane, each fouled with ferric oxide and bentonite clay: one group was ultrasonically cleaned (50 volts for 2 minutes) in the vertically mounted housing; the other group served as a control. During the cleaning period, membranes were rotated 90 degrees every 15 seconds.

Cleaning efficiency was calculated from measurements of the area of membrane cleaned, flux recovery, and weight reductions. To prepare membranes for weight measurements, they were dried in an oven (105°F) for 15 minutes) and desiccator (2 hours). Flux recovery from ultrasonically cleaned membrane samples excised from spiral modules was measured on a flat-cell system.

Results of cleaning tests are given in Table 12. While 90% to 95% of the membrane surface was cleaned for individual pieces of membrane at 100 volts for 2 minutes, only 5% to 7% was cleaned for membranes in one stack. When two stacks were combined, only 1% of the membrane area was cleaned. Thus, it was concluded that the presence of the conventional module materials drastically interfered with the cleaning efficiency of ultrasonics.

Tests (100 volts, 2 minutes with membranes rotated 90 degrees every 15 seconds) were continued using pairs of materials to determine whether a specific spiral component was responsible for the reduction in cleaning efficiency. The results presented in Table 13 show that the percentage of membrane area cleaned for membrane alone was higher (70%) than for membrane and spacer (50%) and much higher than that for membrane and Tricot (10%). Also shown in Table 13, when the spacer was altered by cutting three out of every four crossbars (modified spacer), the membrane areas cleaned increased to 60%. Thus, it appeared that the Tricot may be the major non-membrane culprit in the loss of cleaning efficiency.

Flow Surging Tests

Flow surge tests were conducted to assess the relative impact of unidirectional flow surging (FS), bidirectional flow surging (RD-FS), and flow surging with the permeate flow blocked (BP-FS). For preliminary tests, a freshly fabricated conventional module (no. 11) was used at 500 psi, 0.2 gpm, and 75°F to treat an 18-liter batch of ferric oxide (5 g/l) and residual bentonite clay in RO product water. The flux was allowed to decline roughly 30% prior to testing each remedial cleaning procedure.

With FS, the flowrate was increased from 0.2 to 1.4 gpm, and the pressure reduced to 100 psi (the lowest possible pressure for a flowrate of 1.4 gpm). With RD-FS the position of the entire housing was inverted prior to increasing the flowrate to 1.4 gpm. By doing so, the module itself was not disturbed. BP-FS was tested by occluding the permeate line (at 200-psi operating pressure) prior to increasing the flow through the module.

The results are presented in Figure 23 and Table 14. The flux recovery due to FS in one direction averaged 28% (range of 23% to 32%). Reversing the fluid transport direction while flow surge cleaning yielded comparable results: an average flux recovery of 26% (range of 10% to 36%). The BP-FS caused a 28% (range of 18% to 36%) flux recovery on the average. The net change in flux for each of the three methods was approximately a 37% decline.

Another conventional module (no. 12) was fabricated to serve as a control in further tests. The results obtained from operation of the two modules in parallel and under conditions similar to those cited above are plotted in Figure 24. FS every 2 hours (total of 15 flow surges in 31 hours) was initiated through module no. 11 while flow and pressure were reduced to zero within the control module during those flow surges. The module exposed to a severe flow surge yielded, on the average, a 1.4-gfd flux recovery--almost twice the absolute increase in flux that the control exhibited.

Continued operation under the same conditions (Figure 25), yet with more frequent flow surges (every hour for a total of 15 surges in 17 hours) again indicated that sudden increases in the flowrate at reduced pressure does enhance flux. The flow surge caused by reduction of the flow and pressure of the control module created a slightly greater flux enhancement than the intended flow surge to the experimental module. The control averaged 0.68 gfd increase for every flow surge, while the flow surge module averaged 0.53 gfd per flow surge. This confirmed that depressurizing and repressurizing the RO module without increased flow also produces a cleaning effect by itself.

In Figure 26 the data from blocked permeate line cleaning is presented. Seven periods of permeate line occlusion (some of 5-minute and others of 15-minute duration) of the experimental module with no change in flux or pressure exhibited an impact on the flux. The change in flux for the control, also with constant operating pressure and flowrate, was on the average a 0.06 gfd decline while the module whose permeate flow was blocked exhibited an average 0.67 gfd increase. Figure 26 shows a contrast between the intended cleaning effects of the blocked permeate line and the expected flux decline of the control module. Because the flowrate and pressure were not altered, the flux of the control module reflected the influence of gradual fouling which is generally associated with uninterrupted operation. Blocking the permeate line without changing any other operational parameter therefore also created a slight cleaning effect.

PRETREATMENT EVALUATION

As mentioned in the BACKGROUND section of this report, cross-flow filtration was identified as the most viable alternative to replace multimedia or sand filters. The tubular fabric filter (TF^2) was the filter design chosen for further study to determine its application in the cross-flow configuration. The TF^2 filtration media seems a natural for portable mobile equipment because of its lightweight materials, relatively high packing density and low pressure operation. In addition, the fabric's tendency to flex during flow pattern and pressure changes makes it

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easier to clean the fabric tubes from waterborne contaminants than other rigid filter designs. Because of the flexibility of the tubular design it was recognized that the TF^2 can be used not only in a cross-flow configuration but also in an internally and externally pressurized mode. These three modes of operation are depicted in schematic form in Figure 27.

As shown in cross-flow operation, the contaminated water is constantly being flushed past the inside of the fabric tubes while purified water travels radially outward through the tubes. Sludge removal occurs continuously because turbulent flow conditions push contaminants around the flow loop.

In externally pressurized operation, the contaminated water enters the chamber surrounding the fabric tubes while purified water travels radially inward through the tubes. Sludge is removed intermittently as needed. The tubes are cleaned by pressurizing the clean water outlet and "blowing" the contaminants off the flexing filter media. This mode of operation has also been successfully used in combination with air flotation to simultaneously incorporate both filtration and air flotation in one process and in one piece of equipment. When air flotation is used, sludge is removed continuously with the foam out the top of the column, although the tubes are cleaned intermittently as described above.

In internally pressurized operation, the contaminated water enters the inside of the fabric tubes while purified water travels radially outward through the tubes. Sludge is removed intermittently by opening a valve at the bottom of the filter media and maintaining turbulent flow conditions through the inside of the tubes.

Because of this inherent flexibility of the TF^2 design, all three modes of operation were tested. In addition, three different fabric types were evaluated.

Fabric Types

The simplest type of fabric (Type I) was a coarsely woven polyester material. The webbing was easily visible, but holes through the webbing were not. The Type I fabric was woven into a tubular shape without a seam. The second type of fabric (Type II) woven very finely with a barely perceptible webbing and a nominal 1-micron opening, was stitched and glued to form a tube. The third type of fabric (Type III) was a thick fabric coated internally with a microporous membrane, which provided the surface used in filtration.

The fabrics were supplied to UCLA where all of the filtration testing was conducted (Ref 11). These three fabrics were selected in the hope of providing varying degrees of treatment, with Type I being the least efficient, and Type III being the most efficient.

Test Apparatus Description

The filter testing apparatus is shown in Figures 28 and 29. The unit consisted of an 8-in.-diam plexiglass column which housed one to four fabric tubes. The fabric tubes were 1-in.-diam cut into 4-foot-long lengths, each tube containing 1.0 ft^2 of surface area. The apparatus

was contained on a single, rolling platform. Figure 30 is a schematic diagram of the unit.

To operate the filter, water is introduced into the "tap" water reservoir to a convenient volume. Water is then pumped by the feed pump (a Viking gear pump with variable speed DC motor) through a calibrated rotometer and check valve. Detergent solution and standard test road dust is also injected into the tee, using a variable speed peristaltic metering pump. The concentration of contaminants introduced into the feedwater can be controlled by the metering pump speed or by the concentration in the contaminant reservoir. Normally 88 grams of road dust and 380 grams of military detergent were added to 40 liters of water to make "stock" contaminant solution. This synthetic laundry wastewater flowed through a second, larger rotometer to the top of the column. The wastewater can be injected into the center of the fabric tubes or to the column. The flow split was required in order to evaluate internally, as well as externally, pressurized operation.

Backwash water was introduced into the feed stream prior to the large rotometer. Therefore, the large rotometer indicated total flow to the filter, during normal operation as well as during a cleaning cycle.

The fabric tubes are attached to a header where four filter positions were originally provided.

The bottom header was connected to an electrically operated ball valve. The valve was also equipped with a 3/4-inch manual bypass valve. The discharge side of the ball valve was connected to a backwash collection reservoir and also to a diaphragm pump. The diaphragm pump was used for backwashing and also for externally pressurized operation.

The filtered product water was drained from the column using an overflow device which maintained the liquid level above the level of the filters.

Analytical Methods

The basic analytic method used during all testing to evaluate performance was turbidity. Turbidity was originally measured using a Hach model 2100 turbidity meter, but later a Fischer model was used. Surface tension measurements (du Nouy method) were also made, but liquid surface tension was virtually unchanged during filtration as was total organic carbon measurements. Flow rates and pressure drops were also measured during each test.

Modes of Operation

As previously described, the filter was operated in three different modes. The first mode was internally pressurized (called "closed-ended") during the tests; that is, both the electrically operated ball valve and the bypass valve were closed. The entire influent had to flow through the filters. The second mode of operation was "cross flow," where a portion of the influent flows past the fabric and into the backwash container. The cross-flow rate is controlled by opening the bypass valve. Additionally, very high cross-flow rates can be obtained by using the backwash pump. In the third method, externally pressurized, the influent was introduced to the column outside the filters and forced through the filters by the sucking action of the diaphragm pump.

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Modes of Backwashing

The filter was operated with three different backwashing techniques. The first technique was to cross-wash the filter with very high cross flows in the hope of scouring filtered material from the internal surface of the tubes. To achieve high cross-flow rates the ball valve was completely opened. The cross-flow backwash was used with the internally pressurized and cross-flow filtration modes.

The second type of backwash (also used with the described operational modes) used the diaphragm pump to suck effluent in the plexiglass column back through the fabric so that filtered material would be removed from the internal surface of the tubes.

The third mode was used only with externally pressurized operation. The tubes are backwashed by simply pressurizing the internal part of the tube.

Other types of backwashing or cleaning procedures were used on a trial basis. For example, flow surging and manual cleaning were periodically attempted.

Test Results

The three modes of filtering and the three modes of backwashing were examined in a systematic way through a series of experiments changing one operating parameter at a time. When it became apparent that an operating mode was of little value, that mode of operation was abandoned. Many of the experiments had to be performed first on a trial basis in order to adjust flowrates and determine appropriate operating pressures. Table 15 shows the entire sequence of experiments performed. The test numbers shown in Table 15 correspond with the test numbers on the graphs in the Appendix. The graphs in the appendix contain pressure versus time for all the tests shown in Table 15.

Cross-Flow Operation. Experiments 1, 4, 5, 6, and 8 were cross-flow experiments using different flow rates and cross-flow backwash rates. The cross-flow method removed approximately 70% of the inlet turbidity; no trend of removal efficiency with respect to flow rate or cross-flow rate could be determined. Experiment 1 shows relatively high effluent turbidity, but this is due to the high inlet turbidity.

The filter typically produced large quantities of product water in the beginning of operation but the production rate gradually declined as the fabric began to plug. Eventually, both the influent and cross flow were being directed to the backwash storage vessel. The pressure generally increased to about 5 psig, but this pressure was controlled by the position of the bypass and the backwash pump control valves. For successful cross-flow operation an automatic flow controller will be needed to make the system pressure rise and force more of the influent through the filters.

Internally Pressurized Operation. This operation allowed the system pressure to rise to any desired value, since the entire influent was forced through the fabric. Operating pressures up to 20 psig were tested intermittently; however, pressures above 10 psig were eventually avoided

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to prevent deterioration of the fabric. Type I filters developed small pin holes at high pressures, thus allowing the influent to shoot out in small jet streams. The seams of Types II and III failed at high pressures. Therefore, most of the experiments were restricted to pressures of 10 psig or less.

Experiments 2, 3, 7, and 9 through 13 were conducted in the internally pressurized mode. In general, this mode of operation produced more filtrate than cross-flow operation, but plugging still occurred. Cross-washing was used to clean the fabric but was only marginally effective. The inside of the Type I fabric is shown in Figure 31.

Externally Pressurized Operation. In this mode of operation, the diaphragm pump was used to suck water through the membranes. A total of three experiments were made; two were trial experiments and the third is shown as test No. 14 in Table 15. Cleaning in externally pressurized operation proved to be very successful. The tubes used in experiment 14 were old and were used in the two trial reverse-flow experiments. The figures in the Appendix show that the tubes were successfully backwashed twice, restoring high filtration rate. In actuality, the tubes used for experiment 14 had been backwashed three times in preceding experiments.

The reverse-flow operation has the following advantages: (1) the feed pump can also be used for backwash, and (2) the backwashing rate needs to be only as high as the feed flowrate.

The success of the externally pressurized operation may be due to the expansion properties of the fabric tubes. In internally pressurized operation, the tubes were pressurized and were visibly stretched, which increased the pores and void spaces in the fabric. Thus, some particles were allowed to penetrate deep into the fabric. Then, during backwashing or cross washing, when the pressure was reduced and the tube shrank, particles were bound in the fabric and effective backwashing was hindered.

Externally pressurized operation is the exact opposite with respect to expanding and shrinking. Filtration occurs when the tube is pressurized from the outside, causing it to shrink around the inner supports shown in Figure 32. During backwashing the tube is expanded, allowing the pores and voids to expand, promoting cleaning.

Externally pressurized operation was slightly less efficient than the other operational modes in removing turbidity. However, it should be noted that the diaphragm pump operates in a pulsating fashion, causing spikes in the velocity of water through the fabric. These velocity spikes could attribute to reduced efficiency. Further testing needs to be performed in a pressure vessel without pulsating flow characteristics.

Fabric Types. The effects of fabric type on filter performance is not yet clear. Trial experiments with the Type II membrane showed poor results, due primarily to leakage at the seams. Experiment 11 with the Type III microporous, membrane-coated fabric showed the poorest results -- a surprising result since it should have produced the best quality effluent. It was later learned that the end connections of the tubes were inadequate and that leakage occurred around the worm gear hose clamps that held the tubes to the PVC nipples. The leakage was determined by accident when the experiment was repeated with a rebuilt manifold containing ribbed tubing adapters. The static pressure drop

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through the Type III fabrics was approximately 20 psig at 1.0 gpm/ft^2 using the new manifold. The pressures obtained in experiment 11 were never higher than 15 psig due to the leakage problem at the tube's end connections.

Spongeball Cleaning. A coating of dirt collected on the surface of the filter tubes in tests with Type III fabric but this coating could be removed by gently wiping with a soft cloth or sponge. Therefore, it was postulated that spongeball cleaning could be used to restore filter flux. Spongeball cleaning has been used frequently by University of California at Los Angeles researchers with tubular configured RO modules. The filter header was rebuilt in order to allow spongeball cleaning.

The spongeball cleaning tests were inconclusive because the seams of the membranes ruptured at high pressures (>20 psig) allowing unfiltered water to escape into the effluent. The sponge ball cleaning technique, however, appeared to clean the inside of the tubes; a dirt film, observed during the tests, was removed by the spongeball's wiping and scraping motion.

Flux Decline Tests. To determine the improvement that fabric filtration provides for RO, flux decline tests were performed. This test is a modified form of the "fouling factor" test used frequently to evaluate pretreatment techniques.

The test is quite simple and uses Millipore or Gelman 0.45-micron filters in a vacuum filtration apparatus. Samples of both influent and effluent are collected and filtered. The samples are filtered individually, and the volume filtered as a function of time is recorded. High throughput is an indication of low fouling tendency and has been correlated to RO performance.

Figure 33 shows the results of a flux decline test using effluent collected during externally pressurized filtration with fabric Type I. The lower curve is for unfiltered influent, and it plugs the 0.45-micron filter after approximately 450 ml. The effluent produced by the TF^2, however, shows only moderate plugging after 1,100 ml have been filtered. The difference is dramatic.

Comparison of TF^2 and Multi-Media Filter Equipment. The promise for fabric filtration is even more apparent when one considers the tremendous area and weight savings offered by fabric filters. To show the potential savings, a series of calculations is presented. These calculations are based on using a fabric filter with thirty-six 1-inch filter tubes per square foot of superficial filter area or filter housing area, which corresponds to a center-to-center tube spacing of 2 inches. At this spacing a filtration rate of only 0.139 gpm/ft^2 in the fabric filter (an extremely low loading rate) is necessary to correspond to 5 gpm/ft^2 with a multi-media filter (a moderately high loading rate for this type of filter). It should be noted that lowering the filtration loading rates of a filter (measured in gpm/ft^2) corresponds to longer filtration runs between cleaning cycles and results in generally better overall performance. To illustrate the area savings of the tubular fabric filter over a sand or multi-media filter, Table 16 shows a series of typical multi-media filter flows and the equivalent flow needed in the tubular

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fabric filter to utilize the same superficial filtration area. For example, the filter housing area used in a sand filter at 6.0 gpm/ft^2 (approximately the ROWPU multimedia filter flow rate) could be used to produce the same net flow with a tubular fabric flow at only 0.167 gpm/ft^2 of fabric. This low filtration loading rate is far below the rates used during this test program. In reality, a much greater space savings over a conventional sand filter will be realized because the actual loading rate of the TF^2 is between 0.5 and 1.0 gpm/ft^2. To match the TF^2 actual performance, a correspondingly sized sand filter would have to operate at a loading rate over 15 gpm/ft^2. This magnitude of flow is not possible for a conventional depth filter in order to maintain filtration efficiency. Another way of describing the difference between the TF^2 and sand filter production capacities is as follows: assuming a filtration loading rate of 1 gpm/ft^2 for the TF^2 (based upon actual filtration surface area), a filter capacity of 36 gpm can be provided occupying only 1 ft^2 of filter housing area.* A multi-media filter operating at a filtration loading rate of 5 gpm/ft^2 (in this case, the actual filtration surface area and the filter housing area is the same) would occupy 7.2 ft^2 of filter housing area to provide the same filtration capacity of 36 gpm. Therefore, the TF^2 provides 36 gpm/ft^2 of filter housing area while the multi-media filter provides about 5 gpm/ft^2 of filter housing area.

SUMMARY OF TEST RESULTS

Physical Cleaning

Ultrasonic Cleaning. Ultrasonic cleaning of single-layer membrane disks was successful as shown by the contrast between ultrasonic and control flux values, and visual inspection as shown in Figures 18, 19, and 21 from data depicted in Tables 8, 9, 10 and 11.

Using the most highly fouling feedwaters (mixtures of iron oxide and calcium scale and/or iron oxide and bentonite clay), changes in the weight and the visible presence of foulant on the membrane surface following ultrasonic cleaning were repeatedly discernible. The obstacle to successful operation of an ultrasonic cleaning technique was clearly not the absence of ultrasonic cavitation, but the density of the spiral-wound RO configuration.

Tests with individual pieces of membrane and stacks of module materials shown in Tables 12 and 13 led to the conclusion that a spiral-wound modular configuration is not suitable for ultrasonic cleaning if it is comprised of standard materials of construction. The key to success for a spiral design initially appeared to be the selection of improved module materials which are more efficient in permitting the transmission of ultrasonic energy. Further tests revealed, however, that 20 kHz ultrasonic waves up to 250 volts for periods of 5 minutes have little

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*This is equivalent to 36-gpm filtration capacity/ft^2 of filter housing area.

impact on the flux of fouled spiral-wound RO modules, even when fabricated with materials that had relatively high transmission rates when tested individually and in stacks of the spiral-wound material components.

Flow Surging. In early attempts to produce a cleaning effect with ultrasonics at voltages from 10 to 60 volts (0.13 to 46.8 watts) for periods of 1 to 5 minutes, flow surging proved to be more effective. From the results of this series of tests, which are presented in Figure 6, it appeared that the ultrasonic device significantly affected the flux. However, careful examination of the flux peaks revealed that whenever the normal operating conditions were varied, the flux was influenced. The flow surges (FS) caused by shutting off and restarting the RO system during ultrasonic operation appeared to have a significant positive impact on the flux. Therefore, it was concluded that flow surges had the potential to enhance the flux of RO spiral-wound modules.

A comparison of the two modules monitored in Figure 7 clearly reveals the fluctuations resulting from the flow surges. The data display shows almost identical flux increases between the ultrasonically activated module and the control module. Both test modules experienced the same flow surge, but only the ultrasonic module utilized ultrasonic activation. It is evident that flow surging was the dominant membrane-cleaning mechanism during this test.

In contrast to Figures 6 and 7, the data depicted in Figures 8 and 9 show that when the effect of flow surging was minimized there was no flux improvement of the control module. Modest flux enhancement in Figures 8 and 9 was solely due to the ultrasonic activation.

In addition to the successful evaluation of flow surging, it was documented that merely depressurizing the RO module, without causing a flow surge, creates a cleaning effect (see Figures 24 and 25) by the control module's increase in flux during repressurization. Likewise, blocking the permeate line without altering any other operational parameter also created a slight but positive cleaning effect (see Figure 26).

Control Equipment for Automation of Flow-Surge Cleaning. Complete automation of flow surging and permeate line occlusion can be accomplished through piping and valve modifications. Figure 34 represents the process diagram for the existing ROWPU design while Figure 35 shows a schematic of proposed modifications to the ROWPU to be implemented during optimization testing. It is anticipated that this would be the maximum number of modifications necessary, and it is probable that a final design would entail fewer modifications than warranted for test purposes. Valves V_1, V_2, and V_3 and the high pressure pump are in the existing ROWPU piping configuration and would not be added. Valves indicated as V_4, V_5, and V_6 would be added if an automated testing system is implemented. Auxiliary low pressure pumps P_1 and P_2 would be added for testing purposes; however, in a final design all effort would be made to utilize existing pumps already in the current ROWPU configuration.

Pretreatment Evaluation

The TF^2 investigation has shown that tubular fabric filtration holds promise for development using the cross-flow and externally pressurized configurations. Although the tests were performed on an experimental model test apparatus, the series of tests demonstrated that the fabric could be successfully kept clean while operating on a severely contaminated synthetic waste water feedsource. The fabric filters removed well over one-half of the turbidity without chemical additives, and better efficiency is anticipated with more uniform filtration rates.

The potential weight and area savings for the TF^2 over conventional multimedia filters are substantial. Due to the TF^2 filter media packing density and vertical orientation, a unit with 36-gpm filtration capacity can occupy the same size filter housing as a 5-gpm capacity, mixed media filter.

CONCLUSIONS

1. Ultrasonic cleaning is an effective method for removing ferric oxide, calcium carbonate/sulfate scale, and bentonite clay deposits from individual pieces of RO membranes. Ultrasonic cleaning does not appear to be effective, however, when applied to RO membrane in a spiral-wound configuration.

2. Flow surging with and without permeate line occlusion is an effective method for cleaning spiral-wound RO modules fouled by ferric oxide, calcium carbonate/sulfate scale, and bentonite clay deposits. Flow surging is an attractive auxiliary cleaning method for many commonly occurring foulants that are currently removed by administering chemical dispersion or solubility additives.

3. The TF^2 was shown to be an effective surface filter able to be cleaned intermittently when fouled. The TF^2 potentially can produce water quality comparable to that produced by a mixed media filter with substantial savings in weight and filter housing area.

RECOMMENDATIONS

1. It is recommended that flow surge optimization testing be conducted on a full-scale spiral-wound module. When successfully completed, a ROWPU should be modified to evaluate the flow surging technique on a full-scale RO system.

2. It is recommended that the tubular fabric filter be optimized for cross-flow and externally pressurized operation. Once optimized, a 20- to 40-gpm unit should be built and tested in conjunction with a ROWPU with and without the existing multi-media filter within the ROWPU pretreatment system.

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Table 1. Chemical Cleaning Agents[a] for RO Foulants

Foulant	Chemical Cleaning Agent[b]	Source[c]	Recommended Cleaning Procedure
Iron hydroxides	Citric acid solution at pH 2.5 - 4.0	ABCOR	Use at highest available temp. up to 120°F for at least 45 min. at max. rate available up to 10 gpm/vessel
Iron hydroxides	Cleaning Solution A Citric acid (2%) Triton X-100 (0.1%) Carboxy methyl cellulose (0.001%) Adjust pH to 3 with NH_4OH	Fluid systems, UOP	
Iron hydroxides Also: Ni, Cu, Mn hydroxides	Citric acid solution (2%) Na_2 EDTA solution (2%) Adjust pH to 4.0 with NH_4OH	Dupont	
Iron hydroxides Also: Ni, Cu, Mn hydroxides; silicates	Citric acid solution (2%) Adjust pH to 4.0 with NH_4OH	Dupont	
Iron hydroxides Also: Ni, Cu, Mn hydroxides; $CaSO_4$, $CaHO_4P$	$Na_2S_2O_4$ solution (4%)	Dupont	
Fe or $CaCO_3$	H_2SO_4 or HCl solution Adjust pH to 2.0 - 3.5	DOW	Normal operating pressure (Maximum 4 hours)
Fe, Mn or $CaCO_3$	Citric acid solution (2%) Adjust pH to 2.5	DOW	Circulate 0.5 to 1 hour. Flush with permeate and repeat if flush water is not clear (maximum 3 hours)
Fe containing scales	$Na_2S_2O_4$ solution (2%) Adjust pH to 3.6	W.R. Grace	

Continued

Table 1. Continued

Foulant	Chemical Cleaning Agent[b]	Source[c]	Recommended Cleaning Procedure
$CaCO_3$ and other carbonates	Citric or other noncorrosive acid solution Adjust pH to 2.5 - 3.0	ABCOR	
$CaCO_3$	HCl or citric acid solution Adjust pH to 4.0	Dupont	
$CaCO_3$	Nutek NT-500 or NT-600 solution (5%)	Dupont	Circulate 30 to 60 minutes
$CaCO_3$ (severe) or silica	Citric acid solution (2.4%) NH_4HF solution (2.4%) Adjust pH to 1.5 with HCl	DOW	
Salts of Ca and Mg; humic acid	Cleaning Solution B Sodium tripolyphosphate (2%) Triton X-100 (0.1%) Carboxy methyl cellulose (0.001%) Versene-100 (39% solution of EDTA) (2.0%) Adjust pH to 7.5 with H_2SO_4	Fluid systems, UOP	Use at highest available temp. up to 120°F for at least 45 min. at max. rate available up to 10 gpm/vessel
$CaSO_4$ and CaF_2	EDTA solution Adjust pH to 8-9 Citric acid solution	ABCOR	
$CaSO_4$ and $CaHO_4P$	Citric acid solution (2%) Adjust pH to 8 with NH_4OH	Dupont	Circulate, followed by water rinse
$CaSO_4$ and $CaHO_4P$	EDTA solution (1.5%) Adjust pH to 8 with NaOH	Dupont	Circulate, followed by water rinse

Continued

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Table 1. Continued

Foulant	Chemical Cleaning Agent[b]	Source[c]	Recommended Cleaning Procedure
$Al(OH)_3$	EDTA solution Adjust pH to 3.5 to 3.9	ABCOR	
$Al(OH)_3$	Oxalic acid solution Adjust pH to 3.5	ABCOR	
$Al(OH)_3$	NaF solution Adjust pH to 3 to 6	ABCOR	
Aluminum silicates	NH_4HF_2 solution	ABCOR	
SiO_2	NH_4HF_2 solution Adjust pH to 11 with NaOH	ABCOR	
SiO_2	NH_4HF_2 solution (2%)	W.R. Grace ROGA, UOP	
Silicates	SHMP solution (1%)	Dupont	
Silicates and organics	Caustic solution: Adjust Ph to 11 (max) with NaOH	Dupont	
Organics and "silt"	EDTA (2% Versene-100) Triton X-100 (0.1%) Trisodium phosphate (2%) Adjust pH to 7.5 with H_2SO_4 or HCl	DOW	Pressure less than 75 psi, flush for 2 hours, then run with permeate for 15 minutes, temp. less than 35°C (95°F)
Organics	Cl_2 solution (1.0-5.0 ppm residual Cl_2) from hypochlorite or gaseous Cl_2 injection (not for periodic cleaning, only if other methods fail) Adjust pH to 6.5 to 7.5	DOW	Max. time 60 min. circulate for 15 min. then flush, check for free Cl_2 in feed and effluent. If free Cl_2 is not in effluent after 15 min., reflush with fresh solution.

Continued

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Table 1. Continued

Foulant	Chemical Cleaning Agent [b]	Source [c]	Recommended Cleaning Procedure
Organics	Caustic solution; Cl_2	ABCOR	
Organics, humic acid	Biz detergent solution (0.25%) Adjust pH to 9.4	DOW Dupont W.R. Grace	
Organics	Drewsperse 732 solution (1%)	Dupont	
$Pb(OH)_4$	EDTA solution Adjust pH to 3.0	ABCOR	
$Pb(OH)_2$; $Pb(SO)_4$	EDTA solution Adjust pH to 7 to 8	ABCOR	
$Sn(OH)_4$	Oxalic acid solution Adjust pH to 2.5	ABCOR	
$Sn(OH)_4$	NaF solution Adjust pH to 6	ABCOR	
Cr_2O_3	Acidic solution: Adjust pH to 2.5 to 3.0		

Continued

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^{a}NH$_4$OH = ammonium hydroxide
EDTA = ethylenediaminetetraacetic acid
H$_2$SO$_4$ = sulfuric acid
HCL = hydrochloric acid
NaOH = sodium hydroxide
Cl$_2$ = chlorine
Na$_2$S$_2$O$_4$ = sodium hydrosulfite/sodium dithiunite
NH$_4$HF$_2$ = ammonium B. fluoride
NaF = sodium fluoride
Na$_2$EDTA = disodium ethylenediamine tetraacetate

^{b}Triton, Nutek, Versene, Biz, and Drewsperse are trade names.

^{c}Information from ABCOR in Reference 10.
Information from Dupont, DOW, W.R. Grace, and UOP in Reference 12.

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Table 2. Seawater Contaminants Which Are Potentially Detrimental
to Reverse Osmosis Membranes

Detrimental Contaminant or Factor	Detrimental Concentration	Problem on Membrane Performance	Seawater Concentration Range	Pretreatment Necessary For Normal Occurrence
Silt, Sand	Small	Plugging, Fouling	High Near Surf Zone	Yes
Turbidity, Suspended Solids	1 NTU	Plugging, Fouling	Variable	Yes
Biological Material (Algae)	Small	Fouling, Plugging	Variable	Yes
Organics (Color)	Fulvic & Humic Acids, Small	Fouling, Membrane Swelling and Degradation; CA only	Variable	Very Possibly
Oil and Grease	Small	Fouling, Plugging	Variable	Yes
Iron	$Fe^{+2} > 4$ mg/l $Fe^{+3} > 0.05$ mg/l	Membrane Fouling	0.002-0.9 mg/l	Possibly
Manganese	>0.1 mg/l	Membrane Fouling	0.001-0.05	No
pH	<3 >8	Membrane Hydrolysis; CA only	7-8	No
Temperature of Feed	Varies with Percent Recovery, <40°F, >80°F; CA <40°, >113°F; PA	High Temperature Can Cause Membrane Hydrolysis and Compaction; CA only	60°-80°F	No
Silica	125 mg/l	Membrane Fouling	1 mg/l	No

CA = Cellulose acetate membrane

PA = Polyamide membrane

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Table 3. Brackish Water Contaminants Which Are Potentially Detrimental
to Reverse Osmosis Membranes

Detrimental Contaminant or Factor	Detrimental Concentration	Problem on Membrane Performance	Brackish Water Concentration Range	Pretreatment Necessary For Normal Occurrence
Iron	$Fe^{+2} > 4$ mg/l $Fe^{+3} > 0.05$ mg/l	Membrane Fouling	0 - 8.8	Possibly
Manganese	>0.1 mg/l	Membrane Fouling	0 - 3.8	Possibly
Calcium Sulfate Barium Sulfate Strontium Sulfate	Solubility Index Calculation	Fouling, Precipitation Scaling	Variable	Yes
Silica	125 mg/l	Membrane Fouling	10 - 320 mg/l	Possibly
Calcium Carbonate	Solubility Index Calculation	Precipitation Scaling	Variable	Yes
Iron Bacteria	Small	Fouling, Iron Precipitation On Membrane	Variable	Possibly
Hydrogen Sulfide (Gas)	Small	Fouling, Sulfur Precipitation On Membrane	Variable	Possibly No, except if present in ground- water
Swamp Organics	Humic and Fulvic Acids, Small	Fouling, Membrane Swelling and Degradation; CA only	Variable	Very Possibly

CA = Cellulose acetate membrane

PA = Polyamide membrane

Table 4. Specific Gray Water Contaminants Which Are Potentially
Detrimental to Reverse Osmosis Membranes

Constituent	Concentration mg/l	Potential For Causing Problem at Reported Concentration
Aluminum hydroxide	0.5	Low
Ammonium lauryl sulfate	3-14	Low
Calcium carbonate	0.5	Low
Castor oil	12-70	Medium
Castor oil, sulfonated	3-16	Medium
Coconut oil	5-16	Medium
Coconut diethanol-amine	0.3-1	Low
Epithelium cells	10	High
Ethanol	10-50	Low
Ethoxylated alcohol	30	Low
Glycerol	0.8-2	Low
Hair	1	High
Isopropyl alcohol	10-60	?
Kaolin, colloidal	3	High
Kaolinite	70-90	High
Lactic acid	3	Low
Mineral oil	0.2-0.9	Medium
N,N-Diethyl-m-toluamide	5-12	?
Oleic acid	10-30	Medium
Olive oil, sulfonated	1-5	?
Silica flour	50-110	High
Sodium carbonate	240	High
Sodium 4-chloro-2-phenylphenolate	0.3	Low
Sodium dodecylbenzenesulfonate	1-7	?
Sodium fluosilicate	35	Medium
Sodium ortho-phenylphenolate	0.3	Low
Sodium tripolyphosphate	40-45	High
Sorbitol	0.4	Low
Stearic acid	6-17	High
Talc	20	High
Tallow	1-21	High
Triethanolamine	0.5-2	Low
Triethanolamide alkylbenzenesulfonate	0.7-4	Low
Ultrawet 60L	3-14	Low
Vegetable oil	75	High
Zinc Stearate	1	Medium

"?" Indicates insufficient data

Table 5. Classification of Feedwater Contaminants

Contaminant Category	Water Source	Problem	Is Contaminant Removal Necessary?
1. Solid Inorganics			
a) Silt, sand, grit	SW	Plugging,	Yes
b) Heavy suspended solids, turbidity	SW	Fouling	Yes
c) Suspended solids, turbidity	SW, BW, GW		Yes
2. Solid Organics			
a) Biological Material (algae)	SW, BSW	Fouling	Yes
b) Oil and grease, floatables	SW, BSW	Plugging	Yes
c) Emulsions	SW, BSW		Yes
d) Iron bacteria	GW		Yes
3. Dissolved Organics			
a) Swamp organics	BWS, GW	Fouling, membrane	No
b) Organics	BSW, SW	swelling and degradation	No
4. Potential Precipitants			
a) Iron, Manganese	BW, SW, GW	Fouling	Possibly
b) Silica	BW, GW		No
5. Gases			
a) Hydrogen Sulfide	GW	Fouling	No
6. Low Solubility Salts			
a) Barium Sulfate	GW, BW		No
b) Strontium Sulfate	GW, BW	Scaling	No
c) Calcium Sulfate	GW, BW, SW		No
d) Calcium Carbonate	GW, BW, SW		No

GW = Groundwater
SW = Seawater
BW = Brackish Water
BSW = Brackish Surface Water

Table 6. Seawater Composition at Various Locations

Constituent (mg/l)[a]	Sea of Japan	Persian Gulf	U.S.G.S.	Red Sea	Coastline Libya	Kuwait Bay	Arabian Gulf	Denmark "Lab"	Dittmars Average
Na^+	10,200	12,200	10,560	--	12,000	--	--	10,768	10,566
Ca^{+2}	--	480	400	520	520	400	500	408	400
Mg^{+2}	--	1471	1,272	1,464	1,482	1,690	1,665	1,297	1,272
K^+	375	--	380	--	570	--	--	387	380
Mn^{+2}	0.05	<0.05	0.001-0.01	--	0	--	--	--	.001-0.01
Cl^-	16,300	22,500	18,980	22,000	22,825	24,800	23,100	19,360	18,980
SO_4^{-2}	415	3,700	2,560	--	2,245	3,500	3,100	2,702	2,649
HCO_3^-	--	--	142	--	122	150	135	143	140
Fe	0.8	0.9	0.002-0.02	0.2	0	--	--	--	.02-4.0
Silica	2.2	<1	--	0.4	--	5	5	.02-4	.02-4.0
NH_3-N	--	0.5	--	--	--	--	--	--	7.9
Total Hardness	5,350	7,230	--	7,400	7,400	8,050	8,500	--	--
NO_3^-	0.3	--	--	--	--	--	--	--	--
NO_2^-	--	<0.005	--	--	--	--	--	--	--
PO_4^{-3}	--	<1	0.001-0.1	--	0	--	--	--	--
TDS	34,200	45,600	--	41,200	39,710	48,200	42,000	35,174	34,482
pH	--	8	--	8	--	8.8	8.3	--	--
Turbidity (N.T.U.)	0.8	10.7	--	0.5-0.6	--	--	--	--	--
E.C. (μm/cm)	43,780	54,900	--	--	--	76,800	70,500	--	--

[a] Except pH
"--" No data available.
(Ref 7)

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Table 7. Process Technical Capabilities for the Removal of Contaminants

SYMBOLS
0 - NOT VIABLE
P - POSSIBLY
1 - VIABLE
2 - GOOD VIABILITY

SUPERSCRIPTS
a - NECESSARY REMOVAL OF COLLOIDAL SULFUR
b - MANGANESE @ pH > 9
c - WITH PRIOR OXIDATION, Cl_2
d - FOLLOWED BY SOLID REMOVAL PROCESS
? - REQUIRES MORE DATA TO MAKE FINAL DECISION

UNIT TREATMENT PROCESS	SOLID INORGANICS			SOLID ORGANICS				DISSOLVED ORGANICS		POTENTIAL PRECIPITANTS		GASES	LOW SOLUBILITY SALTS			
	Silt, Sand, Grit	Heavy Suspended Solids, Turbidity	Suspended Solids and Turbidity	Biological Material (Algae)	Oil and Grease, Floatables	Emulsions	Iron Bacteria	Swamp Organics	Organics	Iron, Manganese (Wells)	Silica	Hydrogen Sulfide	Barium Sulfate	Strontium Sulfate	Calcium Sulfate ($CaSO_4$)	Calcium Carbonate
PRE-SEDIMENTATION	2	1	0	0	2	0-1	0	0	0	0	0	0	0	0	0	0
PRE-SEDIMENTATION + COAGULATION	2	2	1	1	2	1	0	0-1	0	0	0	0	0	0	0	0
CYCLONE	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0
CROSS-FLOW FILTRATION	2?	2?	2?	2?	1	P	0	P	0	0	0	0	0	0	0	0
MICROSTRAINER	2	1	0-1?	1	0	0	0	0	0	0	0	0	0	0	0	0
TUBE SETTLER	2	1-2	0-1	0	0	0	0	0	0	0	0	0	0	0	0	0
ULTRAFILTRATION	2?	2?	2?	2?	2	2	0	P-1	P-1	1-2^c	0	1^c	0	0	0	0
ROUGHING FILTER	2	2	2	1-2	1-2	1-2	0	P	0	1-2^c	0	1^c	0	0	0	0
MULTI-MEDIA DEEP BED FILTRATION (12 HR CYCLE)	1	1	2	2	1	1	0	P	P	1-2^c	0	1^c	0	0	0	0
MEMBRANE CLEANING (HEATED SOLUTION)	0	0	0	1	1-2	1-2	1	P-1	P-2	0	0	0	0	0	0	P-1
THRESHOLD INHIBITORS	0	0	0	0	0	0	0	0	0	0	1-2	0	1-2	1-2	1-2	P-1
ION EXCHANGE SOFTENING	0	0	0	0	0	0	0	0	0	1-2	0	0	2?	2?	2	2
LIME SODA SOFTENING	1-2	1-2	1-2	1-2	P-1	P-1	1-2	1$^?$	P-1	2	2	0	2	2	2	2
OZONATION	0	0	0	1-2^d	P-1^d	P^d	2	1-2$^?$	P-1	2^d	0	2^a	0	0	0	0
OZONATION + CATALYST (U.V.)	0	0	0	1-2^d	P-1^d	P-1^d	2	P-2$^?$	P-2$^?$	2^d	0	2^a	0	0	0	0
CHLORINATION	0	0	0	1-2^d	P-1^d	P-1^d	2	1$^?$	P-1	2^d	0	2^a	0	0	0	0
DEEP-BED FILTRATION + U.V.	1	1	2	2	1	1	2	0	P	0	0	0	0	0	0	0
AIR STRIPPING	0	0	0	0	0	0	0	1$^?$	P	1^b	0	2	0	0	0	0
COAGULATION + Cl_2 FLOCCULATION + SEDIMENTATION PROCESS	2	2	2	2	P-1	1-2	P-1	1-2	2	1-2	P-1	P-1	2	0	0	0
AIR FLOTATION + PARTICULATE REMOVAL (CROSS-FLOW FILTER)	2?	2?	2?	2?	2?	1-2	1-2	2	1-2	2	0	2	0	0	0	0

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Table 8. Effect of Ultrasonics on the Flux Values of
Membrane Samples Fouled by Ferric Oxide

Sample No.	Precleaning Flux (gfd)	Ultrasonic Exposure (V;min)	Postcleaning Flux (gfd)	Change[a]
IIA	17.1	50; 2	16.3	−0.8
IIB	16.8	50; 2	17.4	+0.6
IIC	17.7	none	18.0	+0.3
IID	17.0	none	16.8	−0.2
IIIA	19.8	50; 2	22.5	+2.7
IIIB	18.5	50; 2	17.3	−1.2
IIIC	15.7	50; 2	21.3	+5.6
IIID	17.3	50; 2	20.8	+3.5
IIIE	16.8	none	18.2	+1.4
IIIF	18.5	none	17.8	−0.7

[a]+ = increase in flux; − = decrease in flux.

Table 9. Ultrasonic Cleaning Efficiency Measured
Visually for Membrane Samples Fouled
by Calcium Salts

Sample No.	Ultrasonic Exposure	Area Cleaned (%)
IA	50 V; 2 min.	22
IB	50 V; 2 min.	26
IC	50 V; 2 min.	45
Average		31
ID	none	0
Ultrasonic Cleaning Efficiency		31 − 0 = 31%

Table 10. Ultrasonic Removal Efficiency Based on
Visual Inspection of Membrane Samples
Fouled by Bentonite Clay

Sample No.	Ultrasonic Exposure	Area Clean (%)	Notes
1	100 V; 3 min	46	Minor membrane damage
2	100 V; 3 min	60	Minor membrane damage
4	150 V; 3 min	78	Major membrane damage
Mean		61	
3	none	0	
5	none	0	
6	none	0	
Ultrasonic Cleaning Efficiency			61 - 0 = 61%

Table 11. Ultrasonic Cleaning Efficiency Calculated
from Flux Values for Membrane Samples
Fouled by Bentonite Clay

Sample No.	Initial (gfd_{max})	Precleaning (fouled;gfd_m)	Ultrasonic Exposure (volts;min)	Postcleaning (gfd_f)
1	6.4	3.4	100; 3	8.5
2	5.9	3.1	100; 3	8.8
3	5.9	2.1	none	2.8
4	6.8	2.6	150; 3	9.7
5	7.5	3.4	none	3.3
6	6.8	3.4	none	2.6

Note:

$$\text{Percentage of flux recovered} = \frac{(gfd_f - gfd_m)}{gfd_{max} - gfd_m} \times 100$$

Percentage of flux recovered, Sample No. 1 = 170%
Percentage of flux recovered, Sample No. 2 = 210%
Percentage of flux recovered, Sample No. 4 = 170%

Table 12. Ultrasonic Cleaning of Single, Double,
and Triple Layers of Membrane

Description	Ultrasonic Exposure (volts; min)	Area Clean (%)
Single membrane disk (TFC 801 RO)	50; 2 100; 2	40 90-95

One stack:
  Tricot, membrane, spacer,
  membrane, and Tricot
	100; 2	5-7

Two stacks:
  Tricot, membrane, spacer,
  membrane, Tricot, membrane,
  spacer, membrane, Tricot
	100; 2	0-1

Table 13. Effects of Tricot and Vexar on Ultrasonic
Cleaning of RO Membrane

Description	Ultrasonic Exposure (volts; min)	Area Clean (%)	Notes
Membrane (TFC 801 RO)	100; 2	70	Membrane damage
Membrane-modified spacer	100; 2	60	
Membrane-standard Vexar feed channel spacer	100; 2	50	
Membrane-Tricot	100; 2	10	

Table 14. Preliminary Flow-Surge Tests

Procedure Tested	Elapsed Time (hr:min)	Minimum Flux (gfd_m)	Final Flux (gfd_f)	Flux Recovered (%)	Net Δ Flux (%)
FS	25:15	10.5	12.3	32	-23
FS	28:45	7.2	9.9	31	-38
FS	44:15	5.5	7.9	23	-51
Average		7.7	10.0	29	-37
RD-FS	49.15	6.6	10.0	36	-38
RD-FS	52:15	8.3	10.8	33	-33
RD-FS	71:15	7.5	9.7	26	-39
RD-FS	73:15	8.4	9.2	11	-43
Average		7.7	9.9	27	-38
BP-FS	74:15	8.5	9.8	17	-39
BP-FS	76:15	8.5	11.2	36	-30
BP-FS	92:45	6.5	9.1	27	-43
Average		7.8	10.0	26.7	-37

Note:

gfd_{max} = 16 (demonstrated before initiation of fouling feed test, Figure 23)

Percentage of Flux Recovered = $\dfrac{(gfd_f - gfd_m)}{(gfd_{max} - gfd_m)} \times 100$

Net Percentage of Δ Flux = $\dfrac{(gfd_f - gfd_{max})}{gfd_{max}} \times 100$

Table 15. Selected Test Summaries

Test No.	Filter Type	Mode of Operation	Mode of Backwash	Flow (gpm/ft²)	Inlet Turbidity	Volume and Time to Plugging* (gal-min)	Average Efficiency Turbidity (NTU)
1	1 (new)	cross flow	cross flow 3.5 gpm/ft²	0.5	20	32-52	7.7
2	1 (new)	internally pressurized	cross flow 3.0 gpm/ft²	2.0	10	72-32	2.9
3	1 (new)	internally pressurized	vacuum	2.0	10	44-24	2.4
4	1 (old)	cross flow	cross flow 3.2 gpm/ft²	2.0	14	11-30	2.8
5	1 (old)	cross flow	cross flow 2.5 gpm/ft²	0.5	11	6.7-26	4.3
6	1 (old)	cross flow	cross flow 4.0 gpm/ft²	2.0	9.0	24-43	1.95
7	1 (new)	internally pressurized	vacuum	2.0	10	40-20	2.5
8	1 (old)	cross flow	cross flow 2.5 gpm/ft²	2.0	10	11-20	2.5
9	1 (new)	internally pressurized	cross flow 3.5 gpm/ft²	0.5	10	62-72	4.6
10	2 (new)	internally pressurized	cross flow 4.0 gpm/ft²	0.5	13	54-76	8.5
11	3 (new)	internally pressurized	cross flow 3.5 gpm/ft²	0.5	12	19-30	11.6
12	1 (new)	internally pressurized	cross flow 2.0 gpm/ft²	2.0	12	58-24	5.7
13	1 (new)	internally pressurized	cross flow 3.5 gpm/ft²	0.5	12	59-62	6.2
14	1 (old)	externally pressurized	closed end 1.0 gpm/ft²	1.0	12		6.2

*Approximate.

Table 16. Required Flow Rate for Mixed Media and
           Tubular Fabric Filters Occupying the
           Same Superficial Working Area

Sand or Mixed-Media Filter (gpm/ft^2)	Tubular Fabric Filter (gpm/tube)*
1.0	0.028
1.5	0.042
2.0	0.056
3.0	0.056
4.0	0.111
5.0	0.139
6.0	0.167
10.0	0.278
15.0	0.417

*gpm/tube = gpm/ft^2.
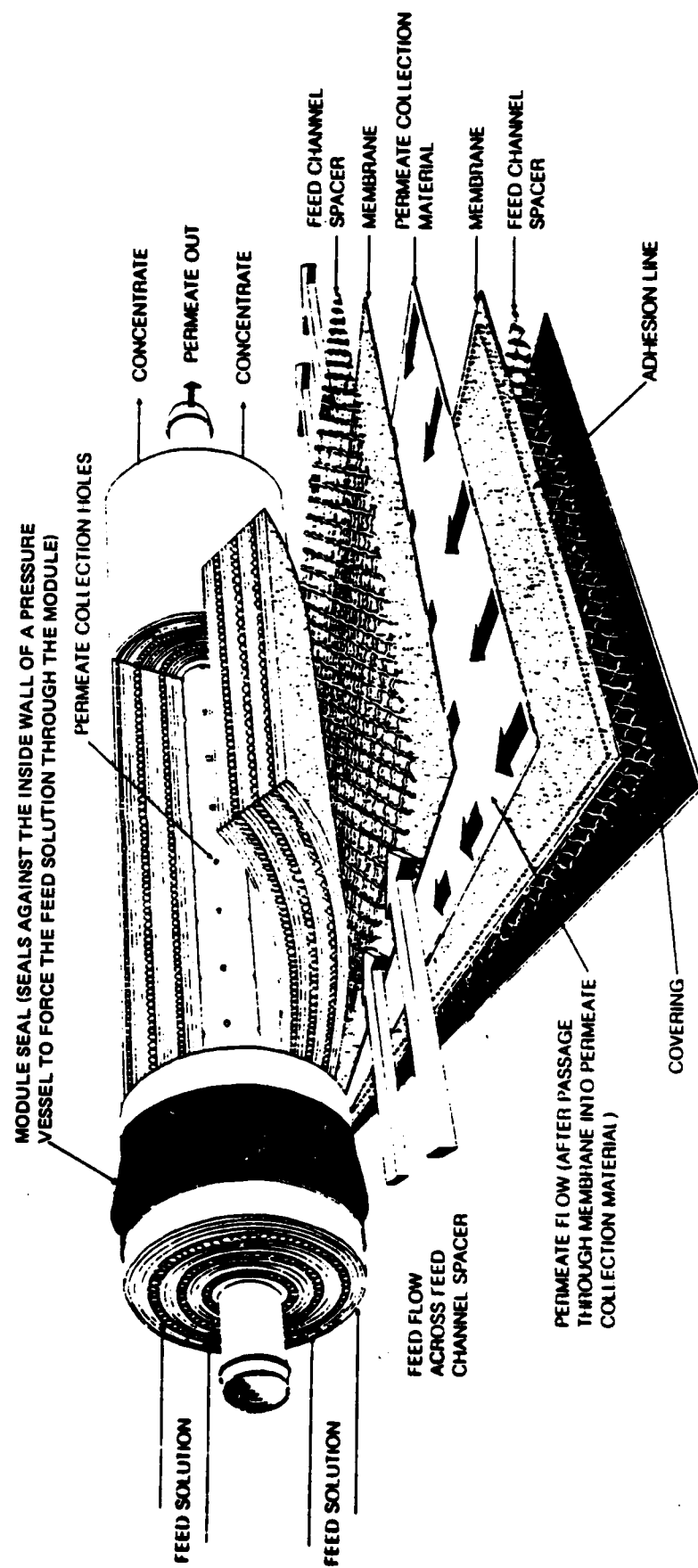
Figure 1. Schematic of the spiral-wound membrane configuration.

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ULTRASONIC TRANSDUCERS

MEMBRANE

POROUS CORE

INFLUENT

PRESSURE VESSEL

LAMINAR SUB-LAYER

ULTRASONIC TRANSDUCER

MEMBRANES AND CORES

PRESSURE VESSEL

INFLUENT
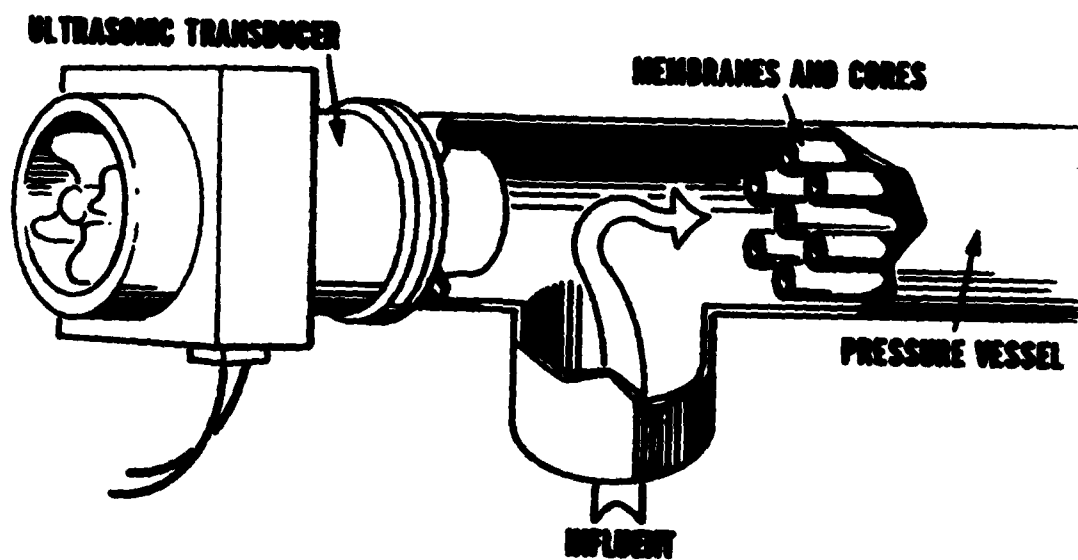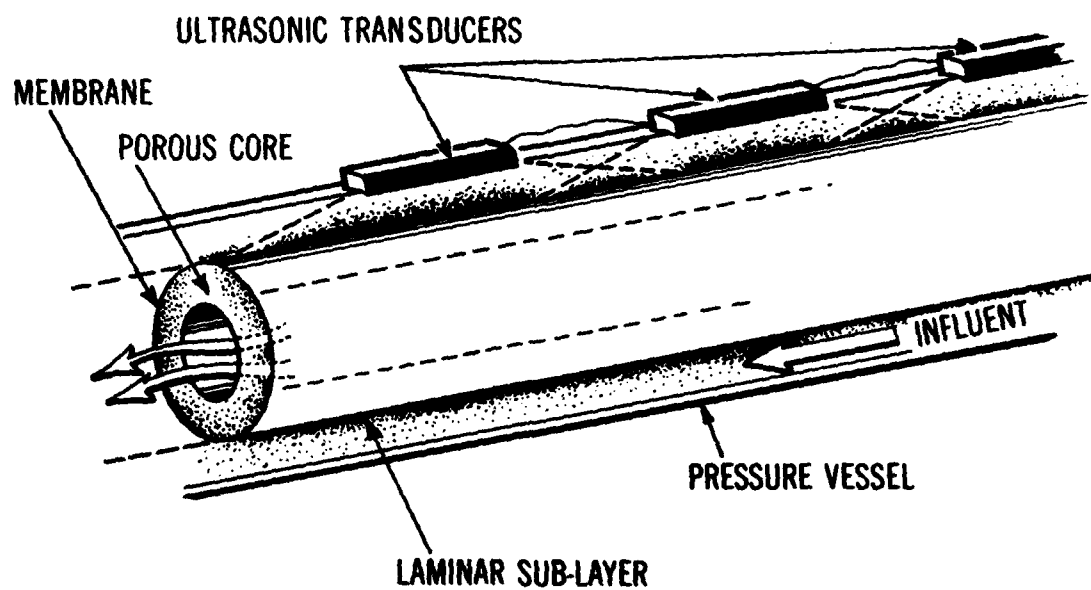
Figure 2. Initial configuration used in ultrasonic cleaning evaluation.

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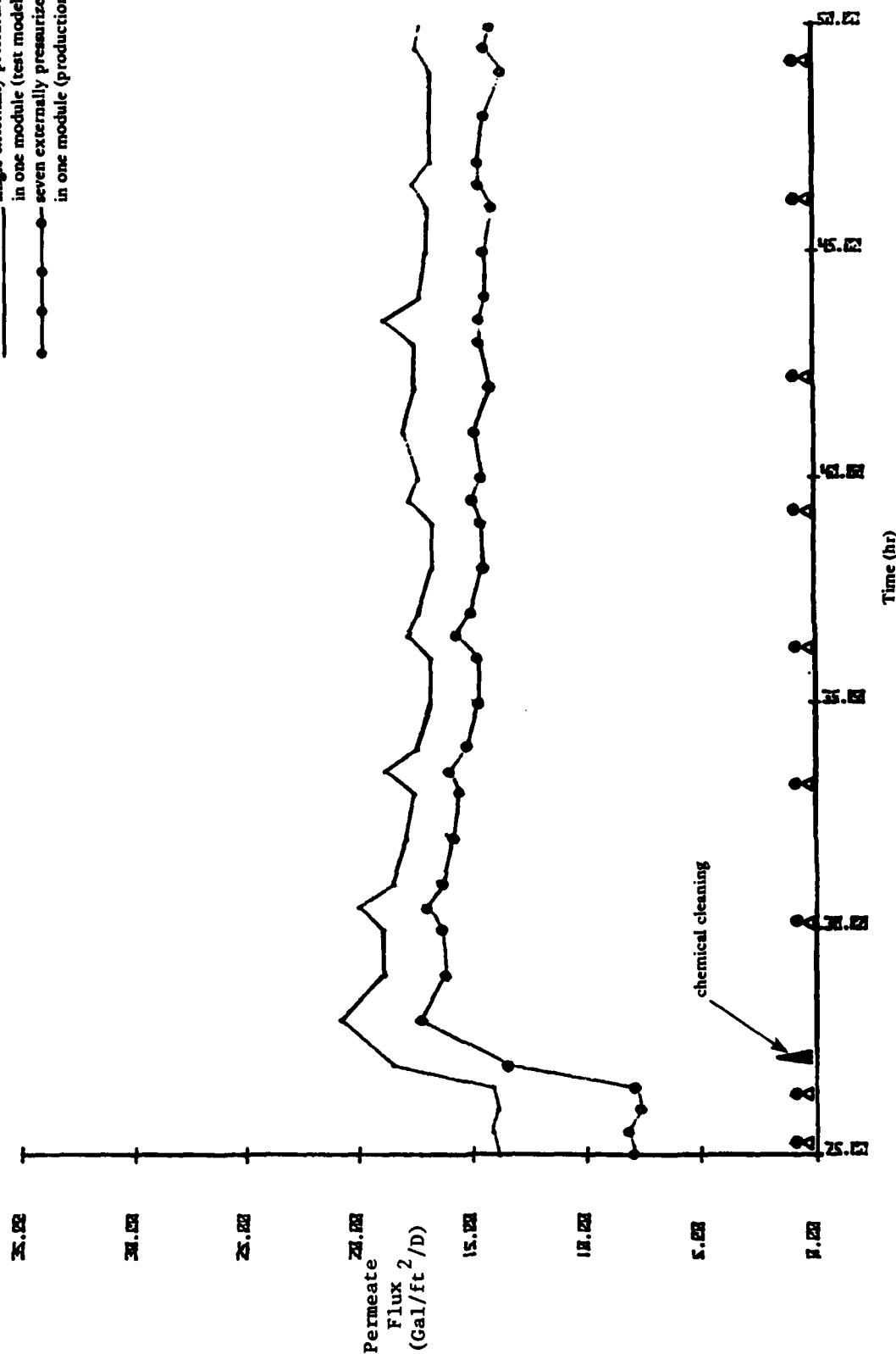
Figure 3. Flow surge with ultrasonics (25 to 26 hours, 300 psi; 27 to 50 hours, 50 psi) (Ref 2).

43
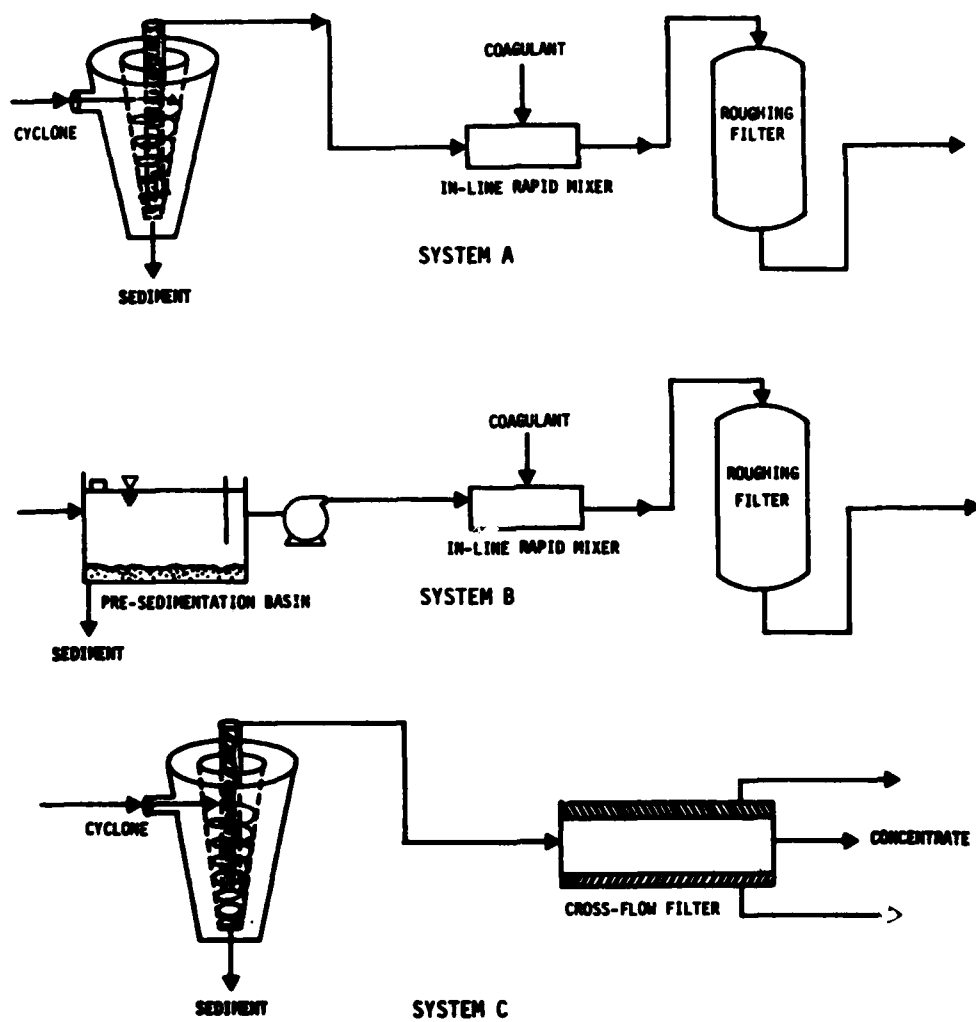
Figure 4. Viable pretreatment systems.
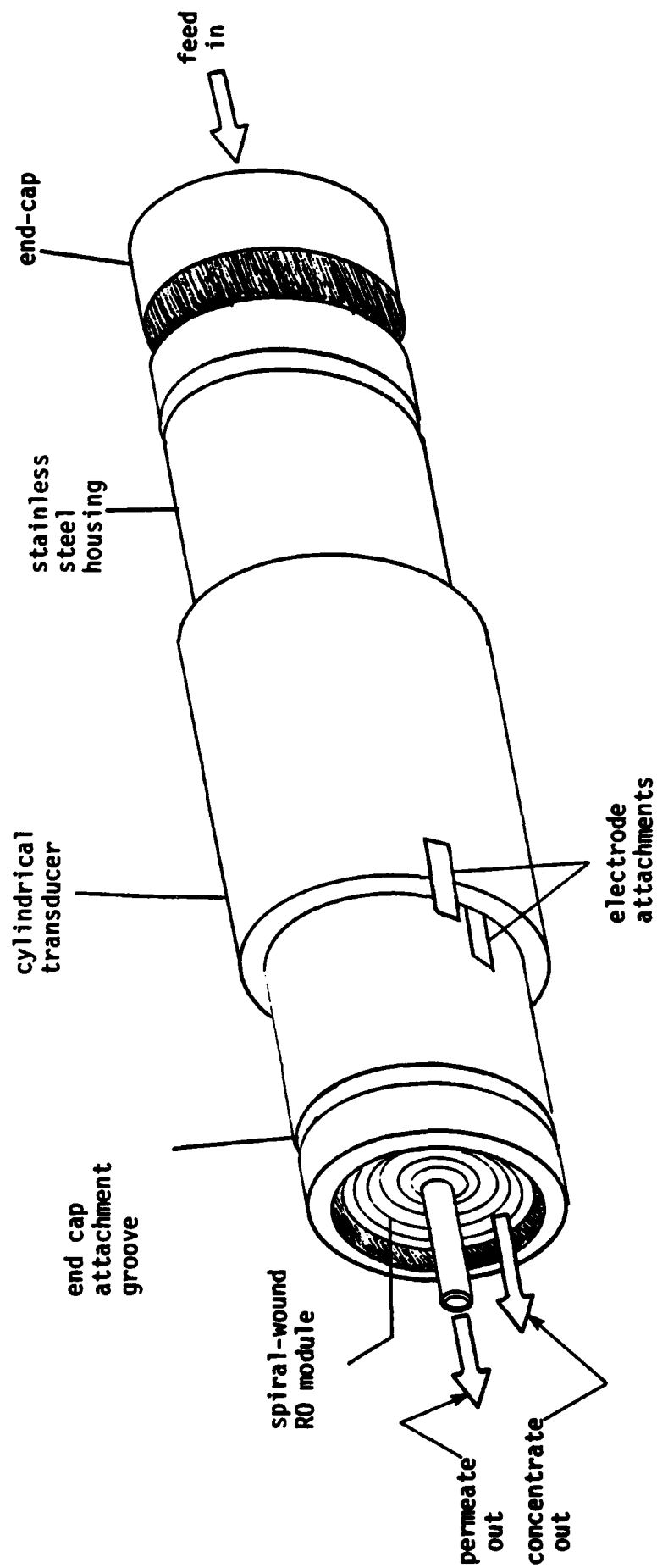
Figure 5. Schematic of cylindrical ultrasonic transducer mounted on reverse osmosis module housing.

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Figure 6. Ultrasonic cleaning at various voltage levels with flow surges.

Normal operating conditions: 600 psi, 0.5 gpm, and 75°F.
Conditions during ultrasonic activation: 0 psi, 0 gpm, and 75°F
unless otherwise specified.

Ultrasonic activation denoted by voltage level and time period.

46

Normal operating conditions: 600 psi, 0.4 gpm, and 75°F.
Conditions during ultrasonic activation: 75°F (pressure and flowrate specified).
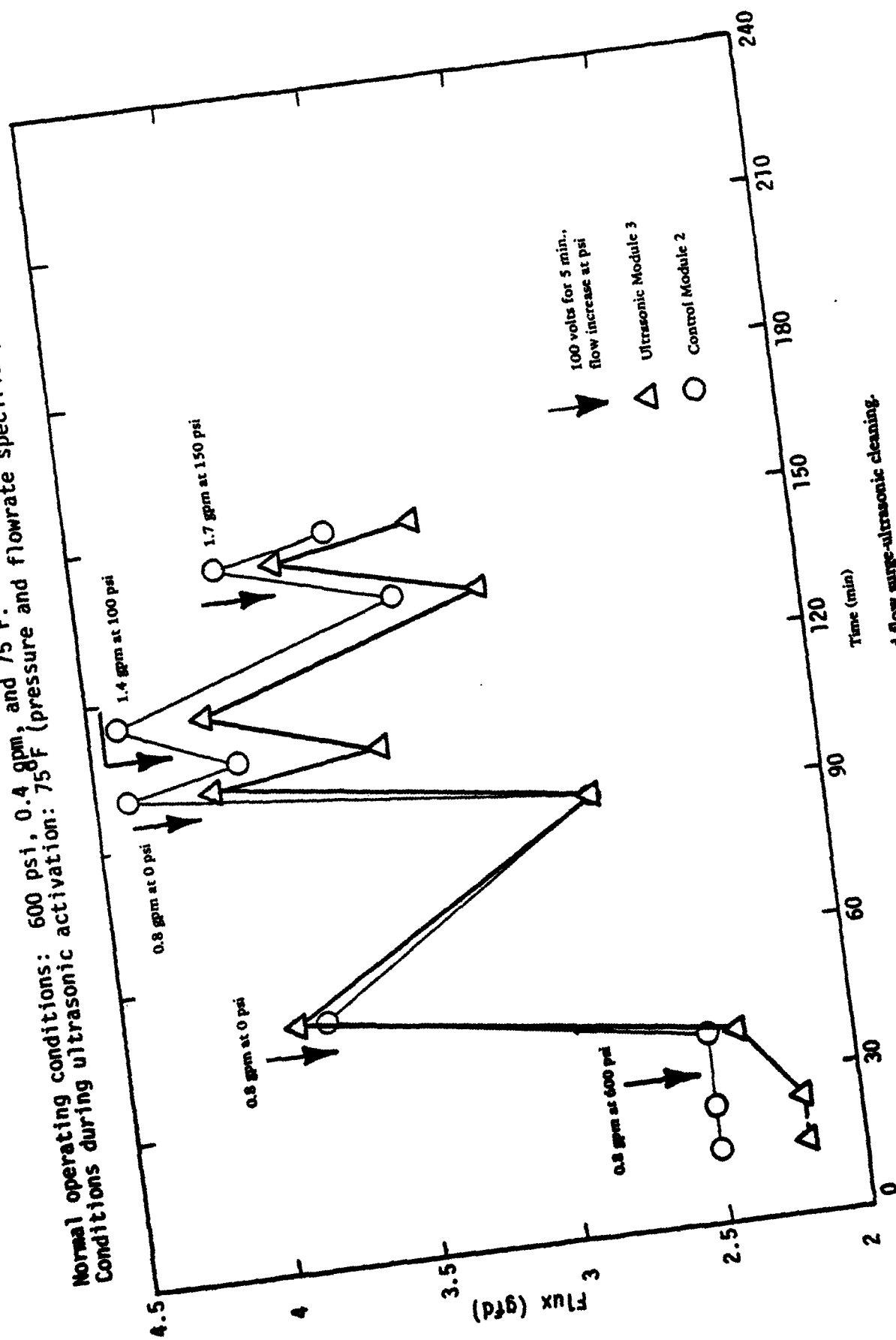
Figure 7. Fouling and flow surge-ultrasonic cleaning.

Normal operating conditions: 600 psi, 0.4 gpm (1-60 minutes) and 0.25 gpm (60-90 minutes), and 75°F. Conditions during ultrasonic activation; same as above.
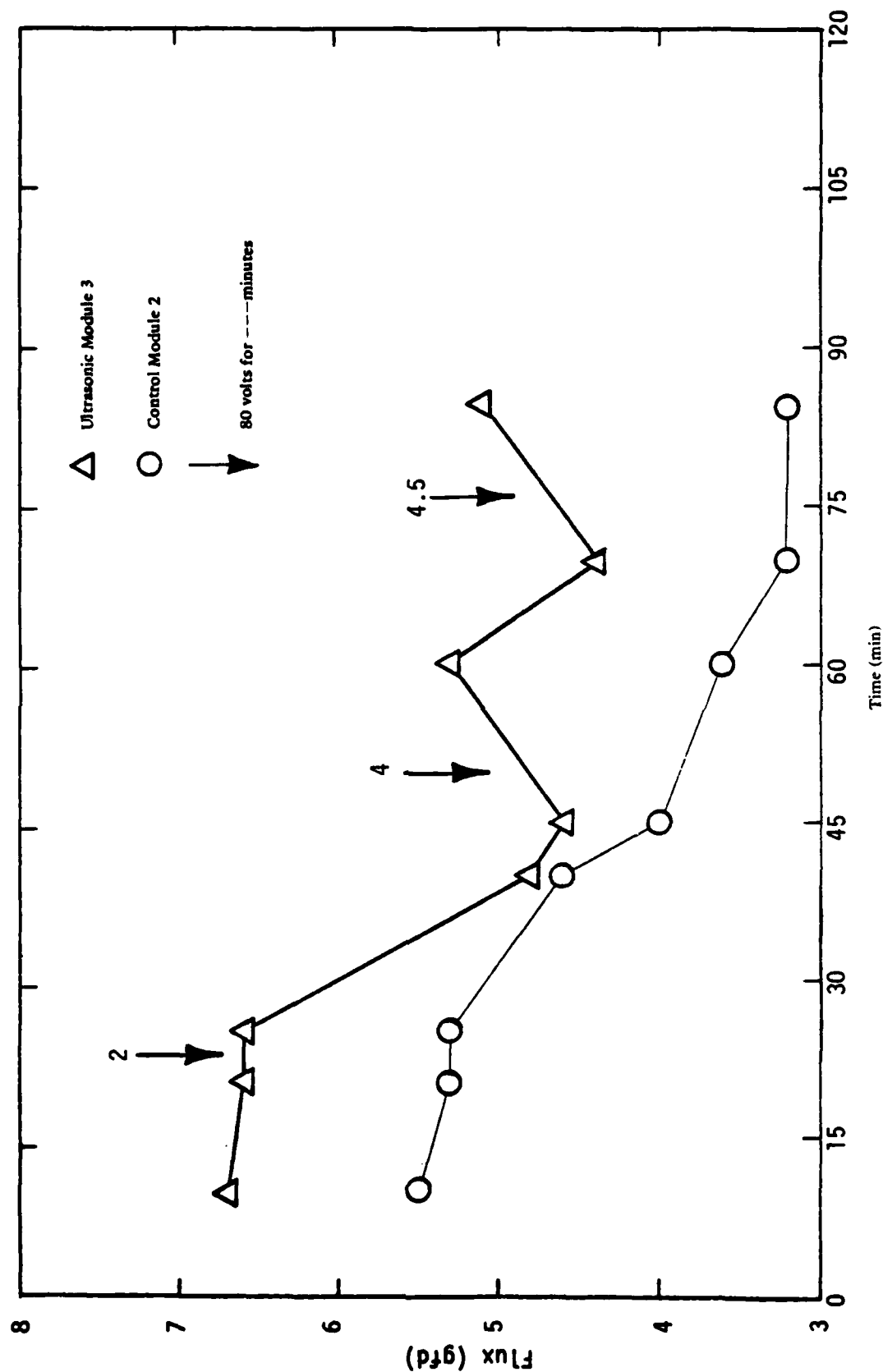
Figure 8. Ultrasonic cleaning at 80 volts without flow surges.

48

Normal operating conditions: 600 psi, 0.4 gpm, and 75°F.
Conditions during ultrasonic activation: 600 psi, 0.4 gpm, and 75°F.

△ Ultrasonic Module 3

○ Control 2

→ 100 volts for 4 minutes

Figure 9. Ultrasonic cleaning at 100 volts without flow surges.

49

Normal operating conditions: 600 psi, 0.4 gpm, and 75°F.
Conditions during ultrasonic activation: 600 psi, 0.4 gpm, and 75°F unless otherwise specified.
The modules were chemically cleaned prior to initiating these tests.
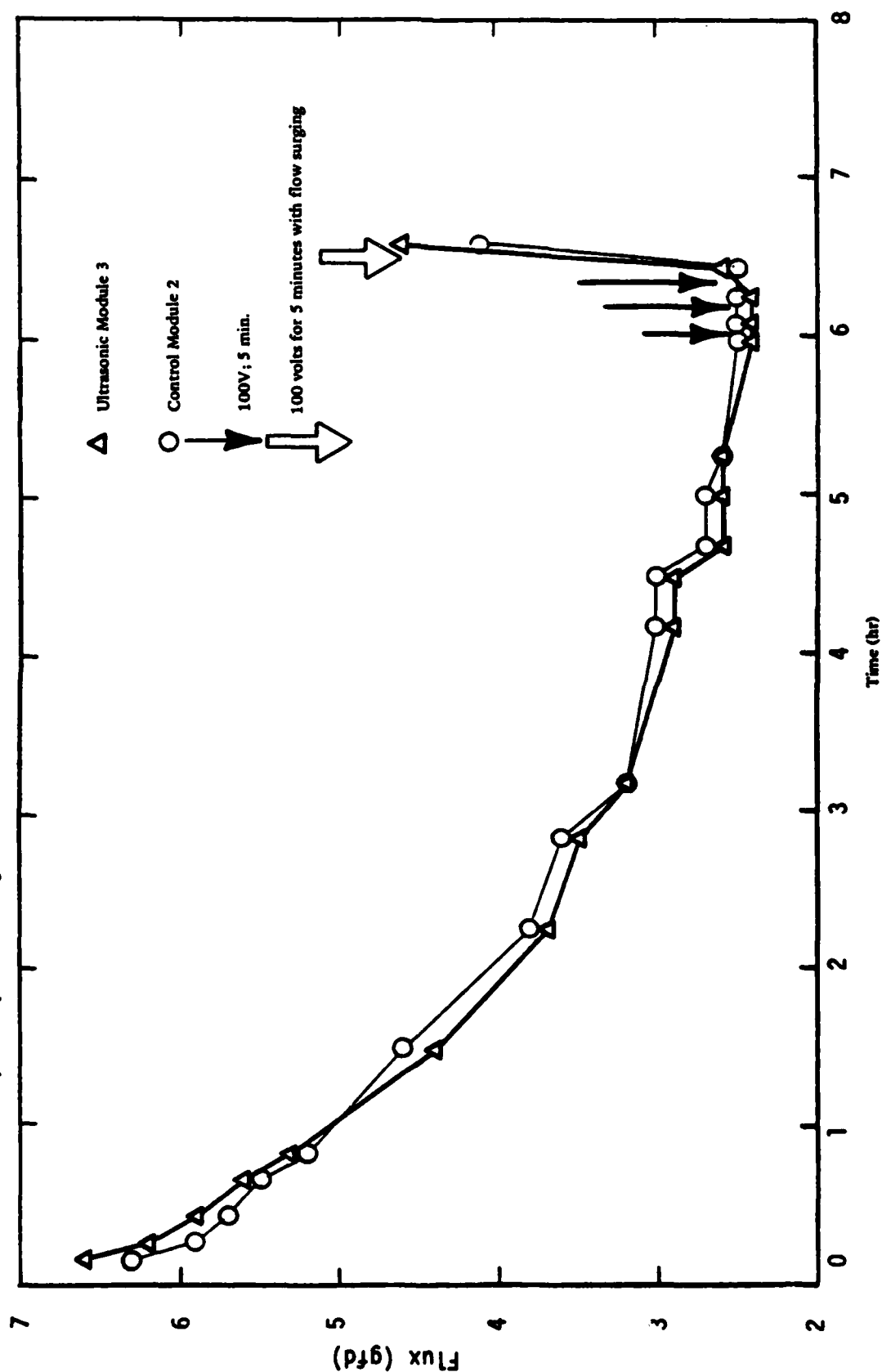
Figure 10. Ultrasonic cleaning at 100 volts with and without flow surges.

50

Normal operating conditions: 600 psi, 0.6 gpm (0-6 hours) and 550 psi, 0.34 gpm (6-18 hours), and 75°F.
Conditions during ultrasonic activation: 0 psi, 0.6 gpm (0-6 hours) and 0.34 gpm (6-18 hours), and 75°F.
Ultrasonic module 5 was exposed to 50 volts (32.5 W) for 2 minutes prior to recording each datum.
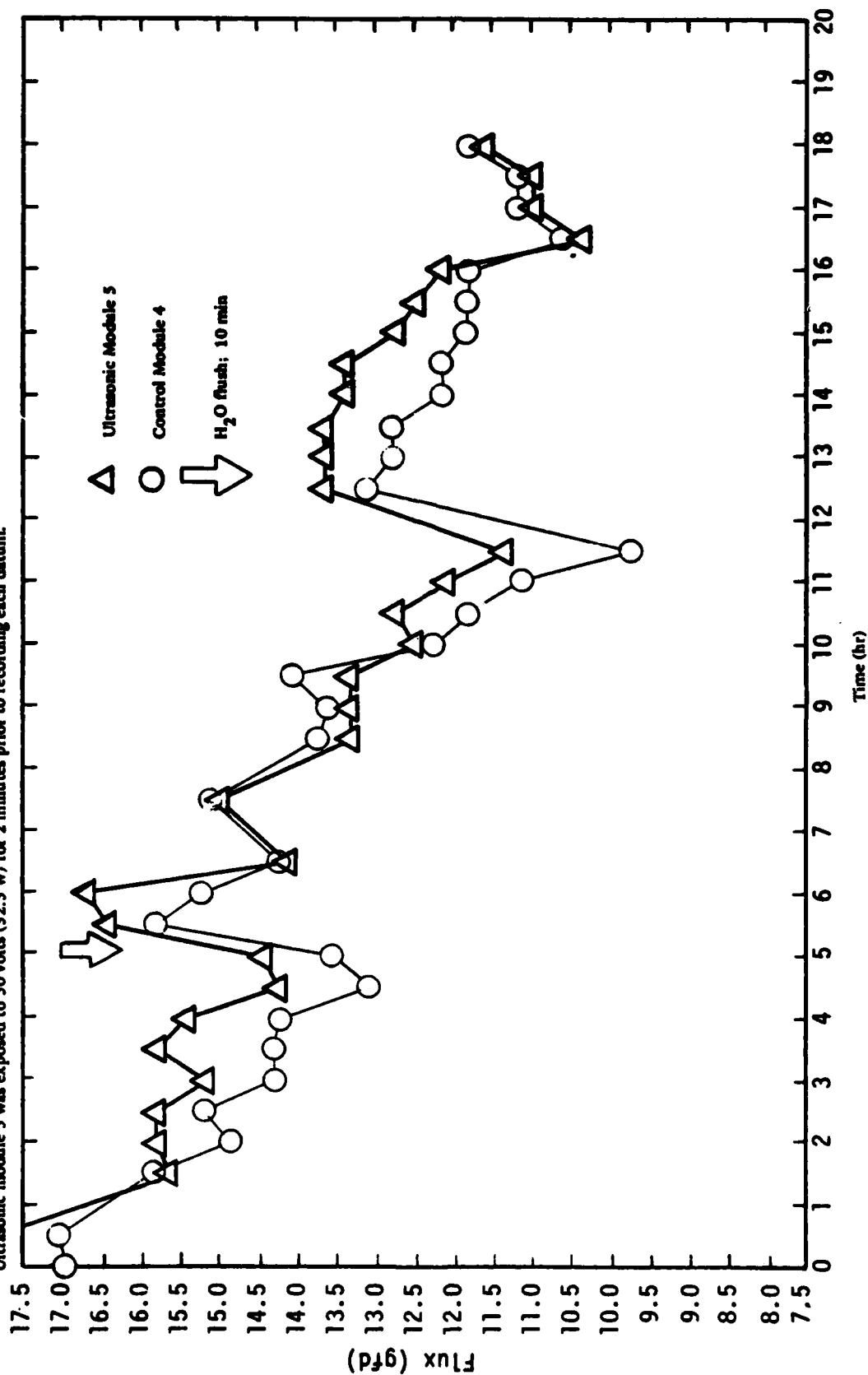
Figure 11. Fouling minimization through ultrasonics at 50 volts for synthetic shower/laundry wastewater.

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Normal operating conditions: 550 psi, 0.48 gpm, and 75°F.
Conditions during ultrasonic activation: 0 psi, 0.48 gpm, and 75°F.
Ultrasonic module 5 was exposed to 80 volts (83.2 W) for 2 minutes.
Flux values for both modules before and after ultrasonic activation are included.

△ Ultrasonic Module 5

○ Control Module 4
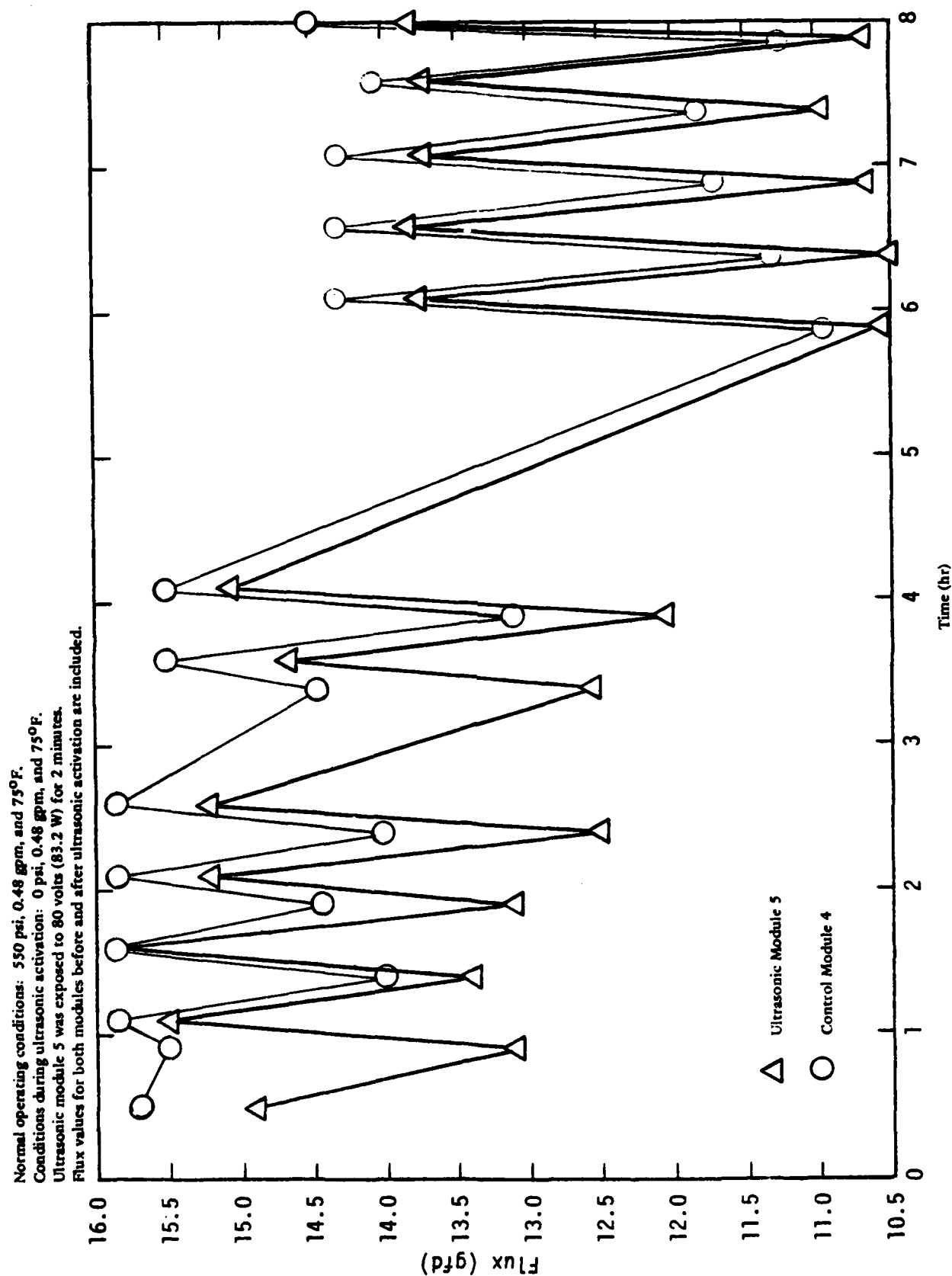
Figure 12. Fouling minimization through ultrasonics at 80 volts for synthetic shower/laundry wastewater.

52
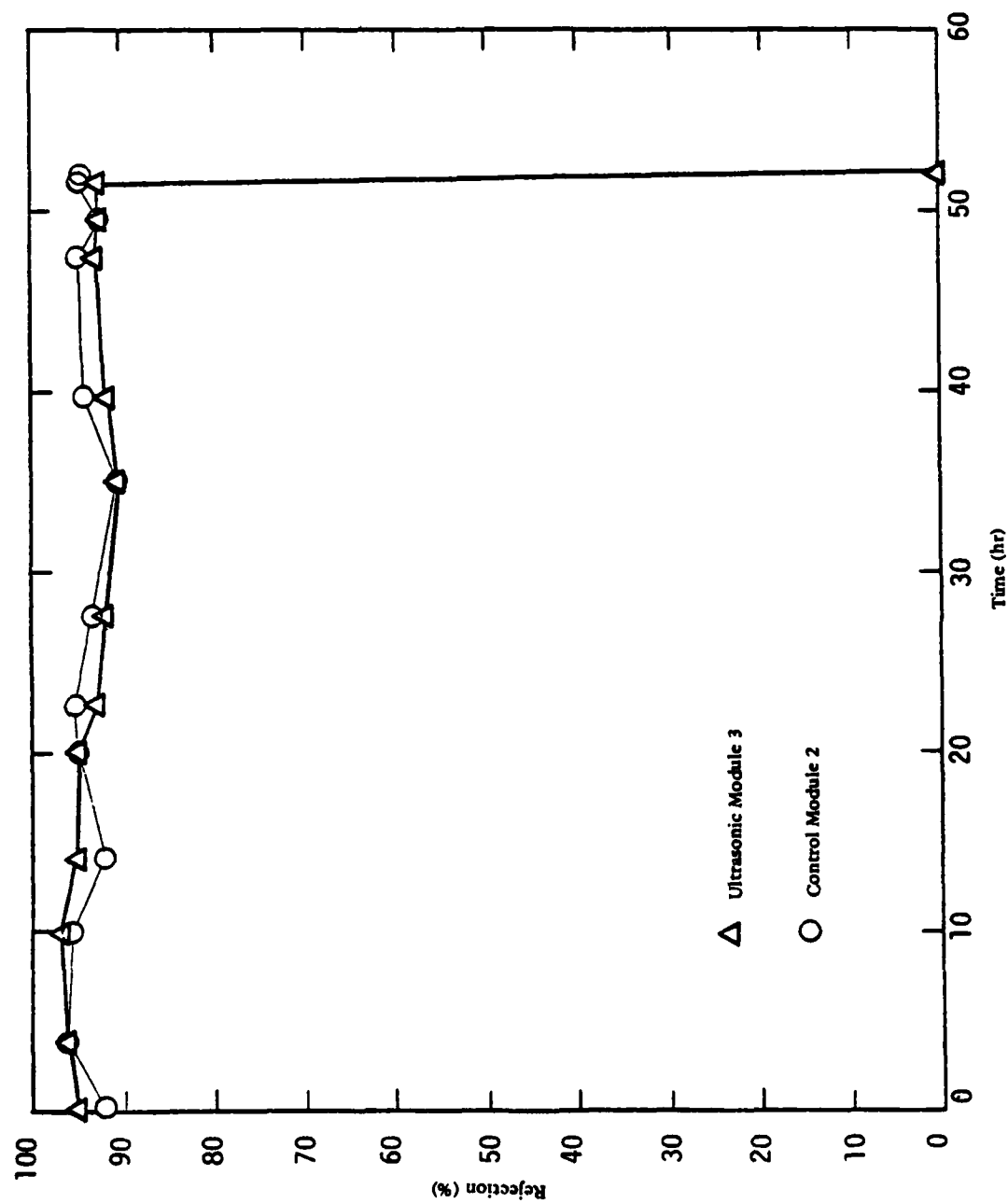
Figure 13. Rejection percentage throughout the 52-hour life of modules 2 and 3.
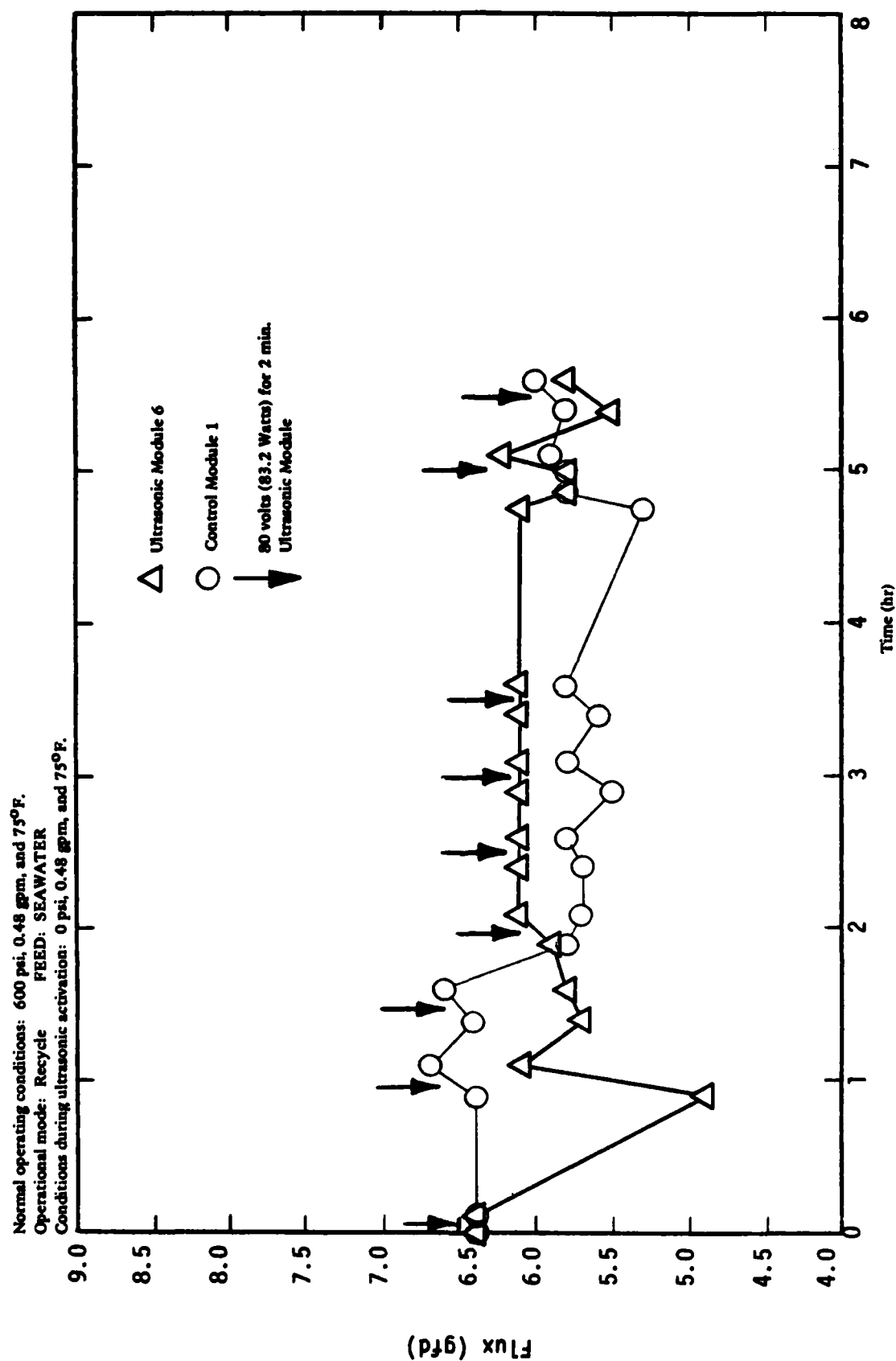
Figure 14. Fouling minimization through ultrasonics at 80 volts.

△ Ultrasonic Module 6

○ Control Module 1
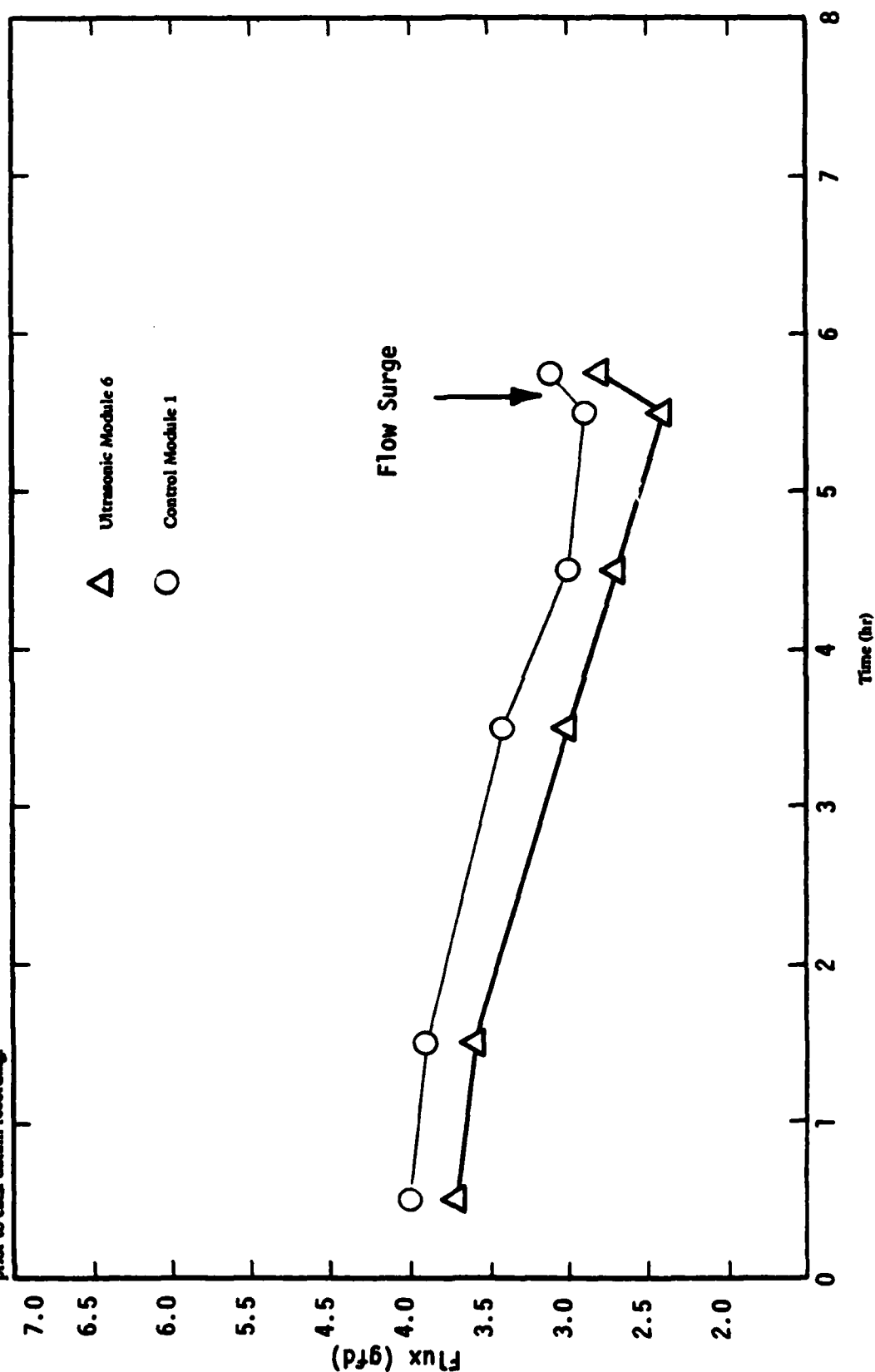
Flow Surge

Figure 15. Fouling minimization through ultrasonics at 80 volts with the following conditions during flow surge:
0 psi, 1.0 gpm, and 75°F.

Normal operating conditions: 675 psi, 0.4 gpm, and 75°F.
Operational mode: Recycle. Feed: Seawater
Conditions during ultrasonic activation: 0 psi, 0 gpm, and 75°F.
The module (i.e., #2) was exposed to the voltage specified below.
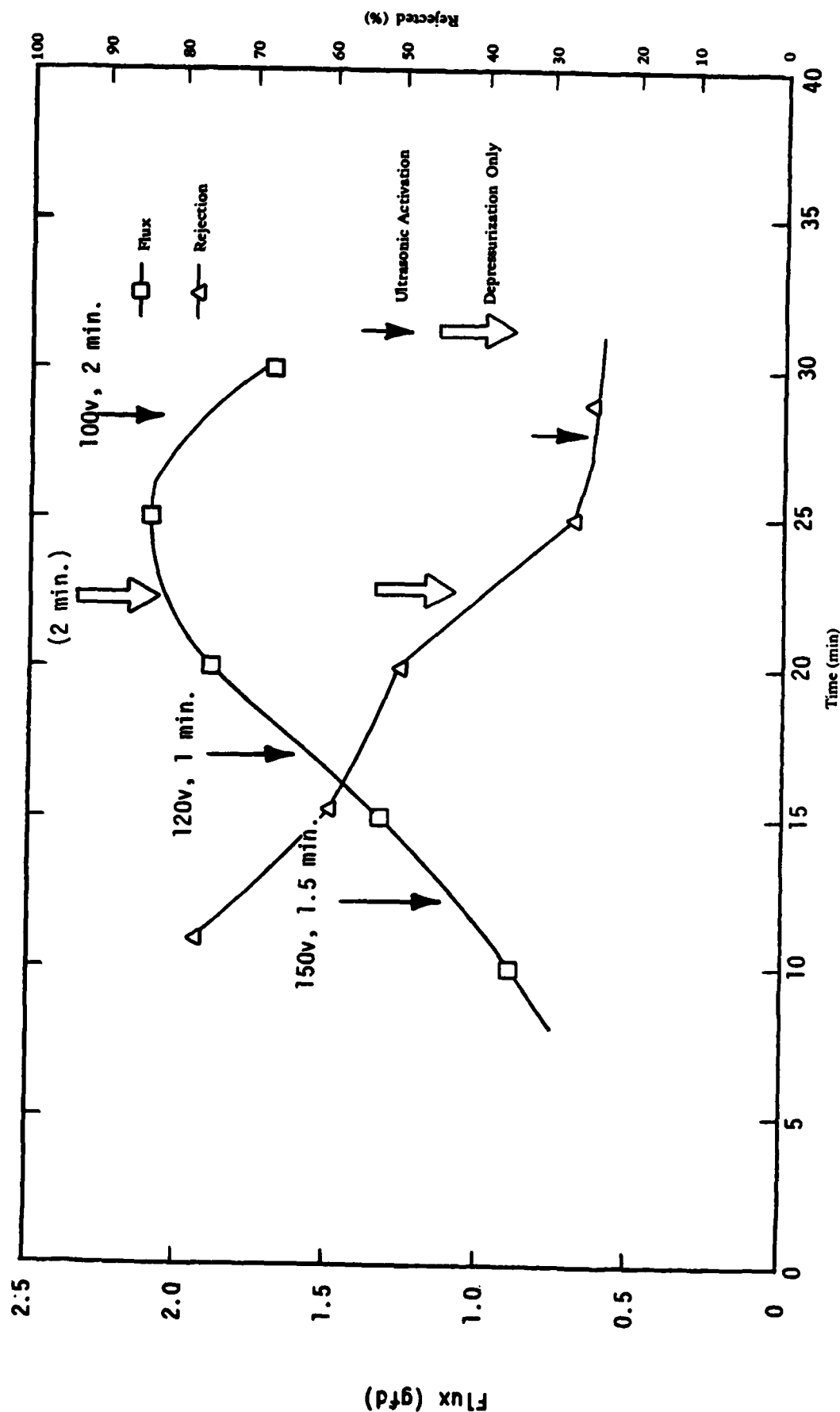
Figure 16. Ultrasonic cleaning at 0, 100, 120, and 150 volts.

56

Figure 17. Ferric oxide fouling of modules 1 and 6.

Normal operating conditions: 600 psi, 0.4 gpm, 75°F.
Operational mode: Recycle   Feed: 5 g/l Fe_2O_3
Conditions during ultrasonic activations: 0 psi, 0 gpm, 75°F.

△ Ultrasonic Module 6

○ Control Module 1

→ Ultrasonic activation: 150 volts for 2 min.

⇨ Ultrasonic activation: 100 volts for 2 min.

Flux (gfd)

Time (hr)

Figure 18. Flux recordings of excised membrane samples fouled by ferric oxide.

Operating conditions: 600 psi and 72°F
Conditions during ultrasonics: 0 psi and 72°F in bench-scale cleaning apparatus

△ III A Ultrasonic   ○ III B No Ultrasonics
▲ III C Ultrasonic   ● III F No Ultrasonics
▲ III D Ultrasonic   □ II D No Ultrasonic

All ultrasonic activation 50V, 2 min.

Sample letters correspond to those used in Table 8.

Flux (gfd)

Initial

Final

58

Group III
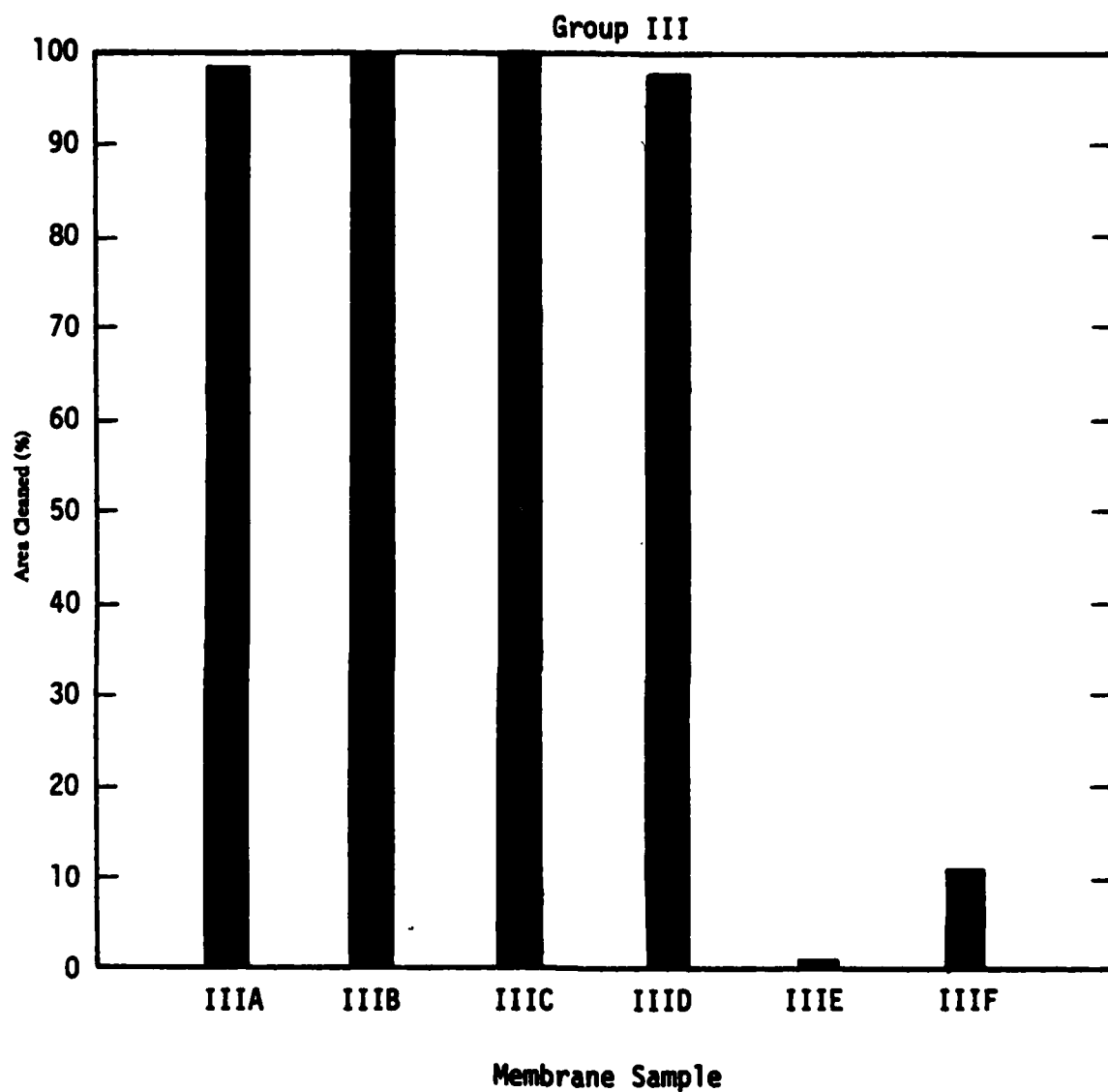
Figure 19. Percentage of area cleaned as measured by visual inspection for membranes fouled by ferric oxide. (Sample letters correspond to those used in Table 8 and Figure 18).

Normal operating conditions: 600 psi, 0.4 gpm, and 70°F.
Operational mode: Recycle   Feed: $CaCO_3$ and $CaSO_4$ in tap water
Conditions during ultrasonic activation: 0 psi, 0 pgm, and 70°F;
a flow surge occurred during start up after each ultrasonic activation.

△ Ultrasonic Module 10

○ Control Module 9

⇨ Ultrasonics: 90 volts, 2 min.

➡ Ultrasonics: 150 volts, 2 min.

➡ Ultrasonics: 100 volts, 2 min.
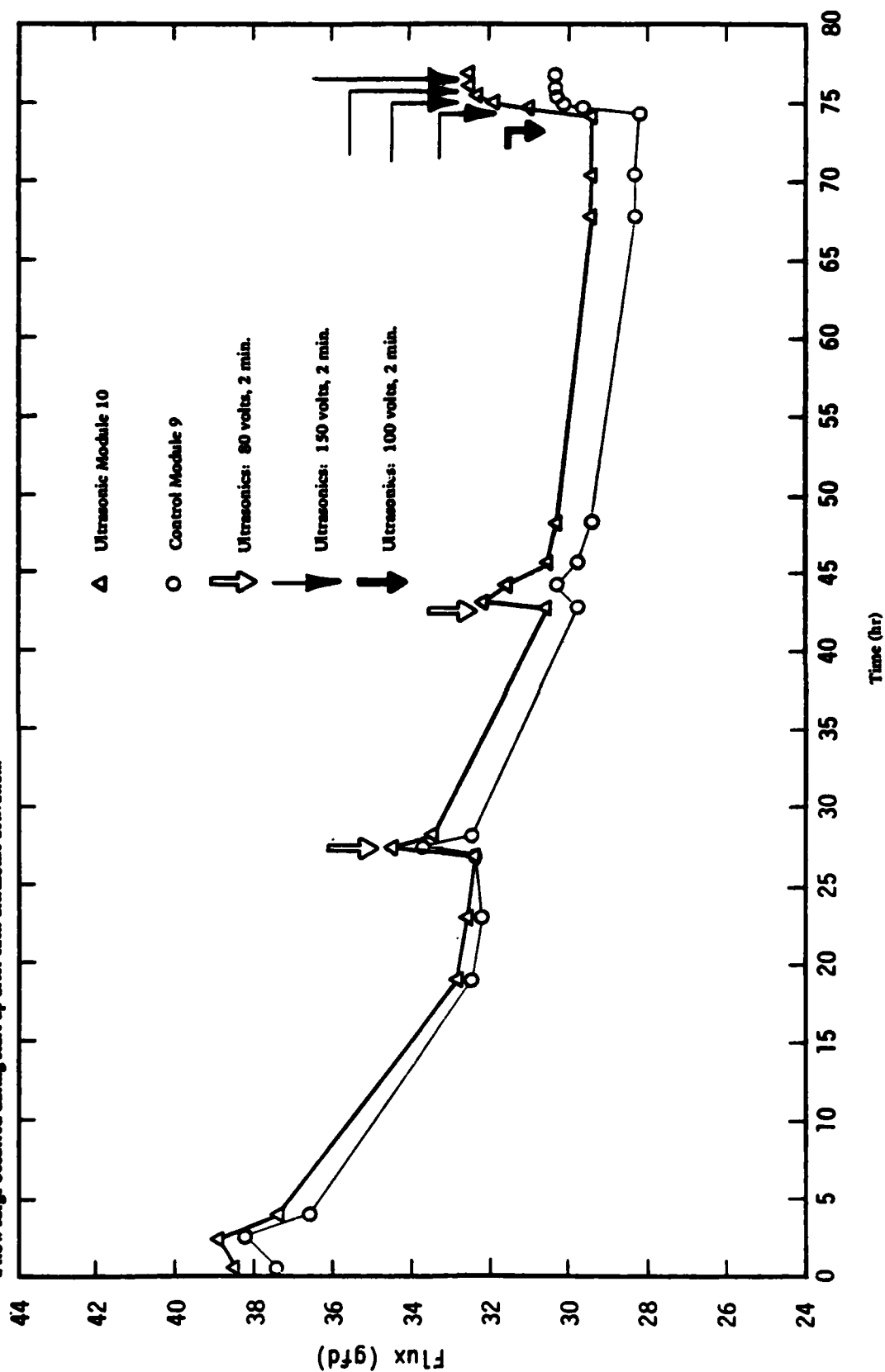
Figure 20. Fouling with calcium carbonate and calcium sulfate.

60
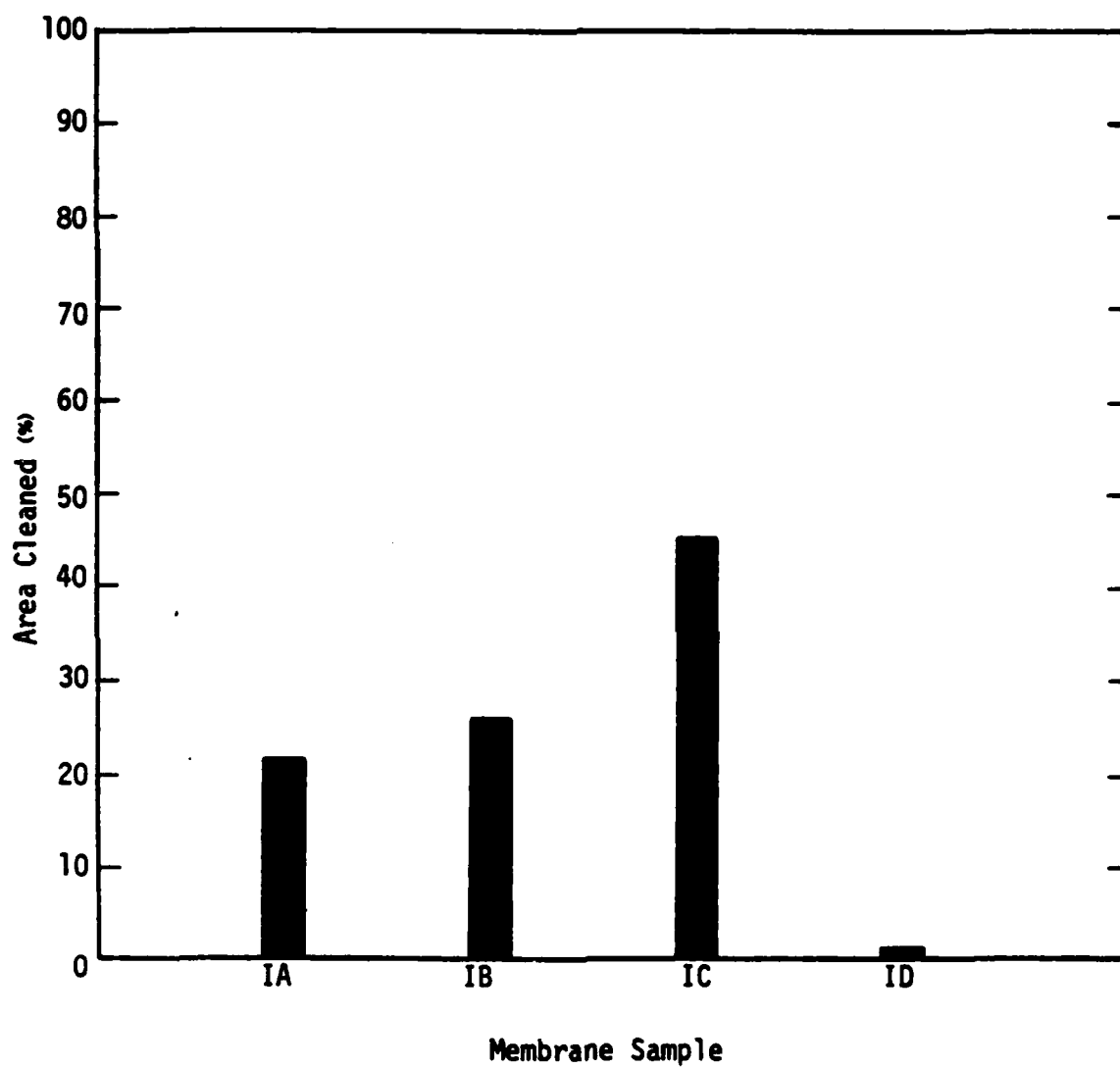
Figure 21. Percentage of area cleaned as measured by visual inspection for membranes fouled by calcium salts. (Sample letters correspond to those used in Table 9).
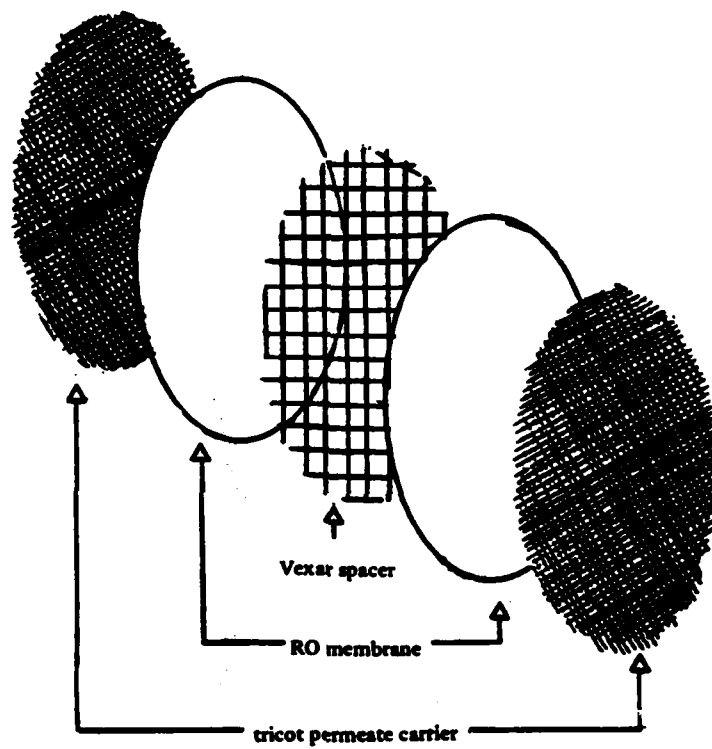
Figure 22. Basic stack for tests in vertical ultrasonic cleaning apparatus.
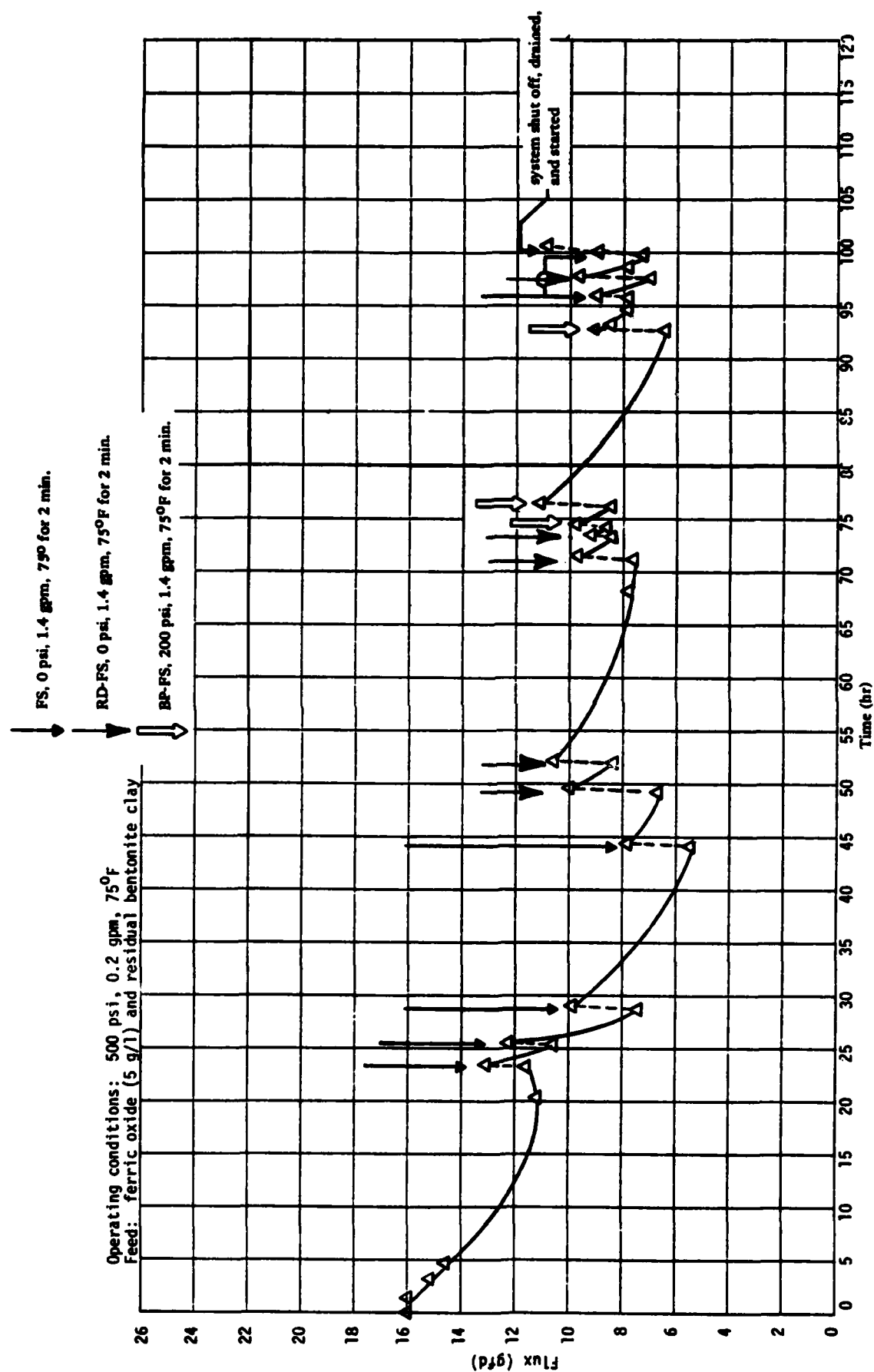
Figure 23. Preliminary flow surge tests.

Operating conditions: 500 psi, 0.2 gpm, 75°F
Feed: ferric oxide (5 g/l) and residual bentonite clay

FS, 0 psi, 1.4 gpm, 75° for 2 min.

RD-FS, 0 psi, 1.4 gpm, 75°F for 2 min.

BP-FS, 200 psi, 1.4 gpm, 75°F for 2 min.

system shut off, drained, and started

63
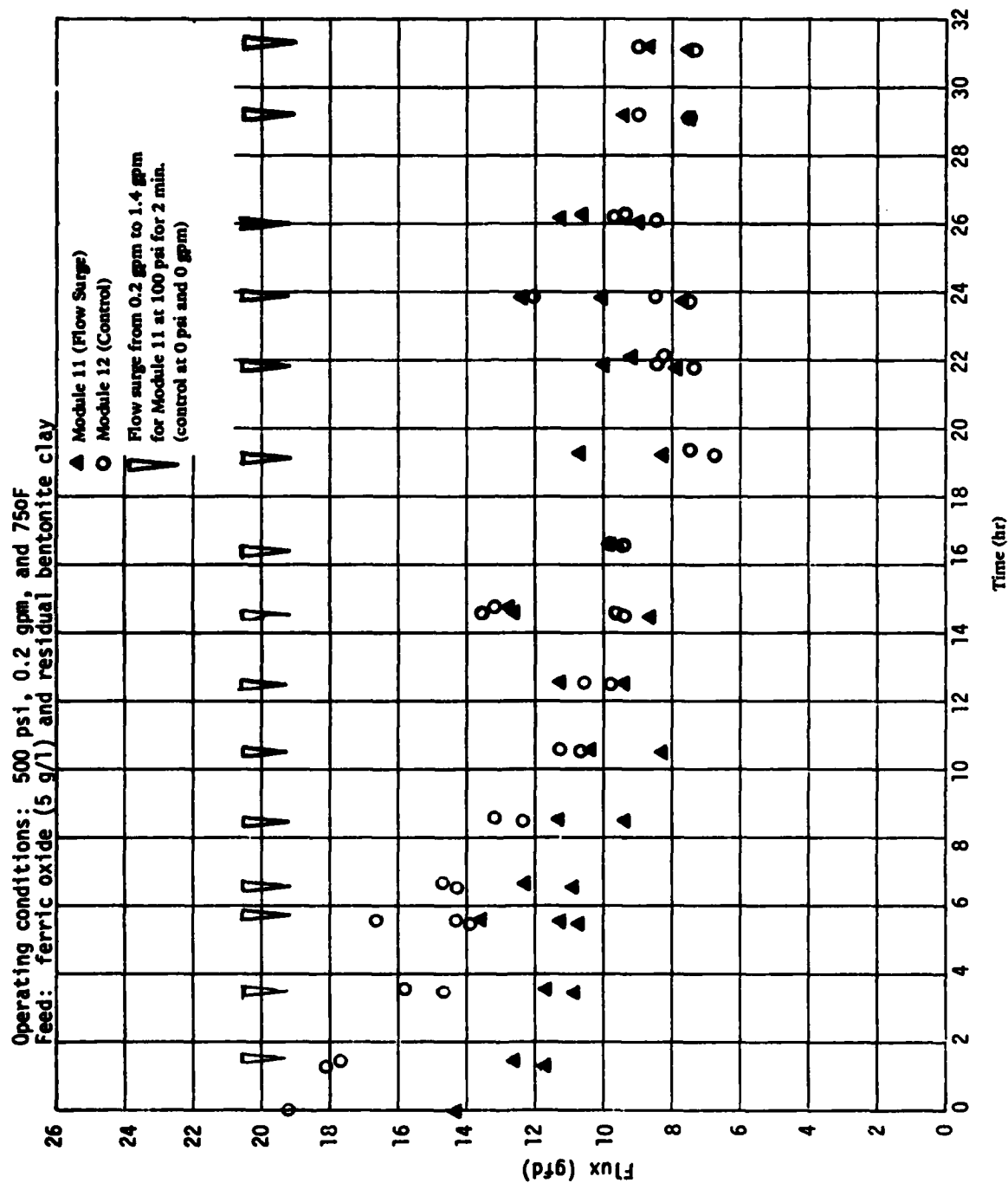
Figure 24. Unidirectional flow surging.

64
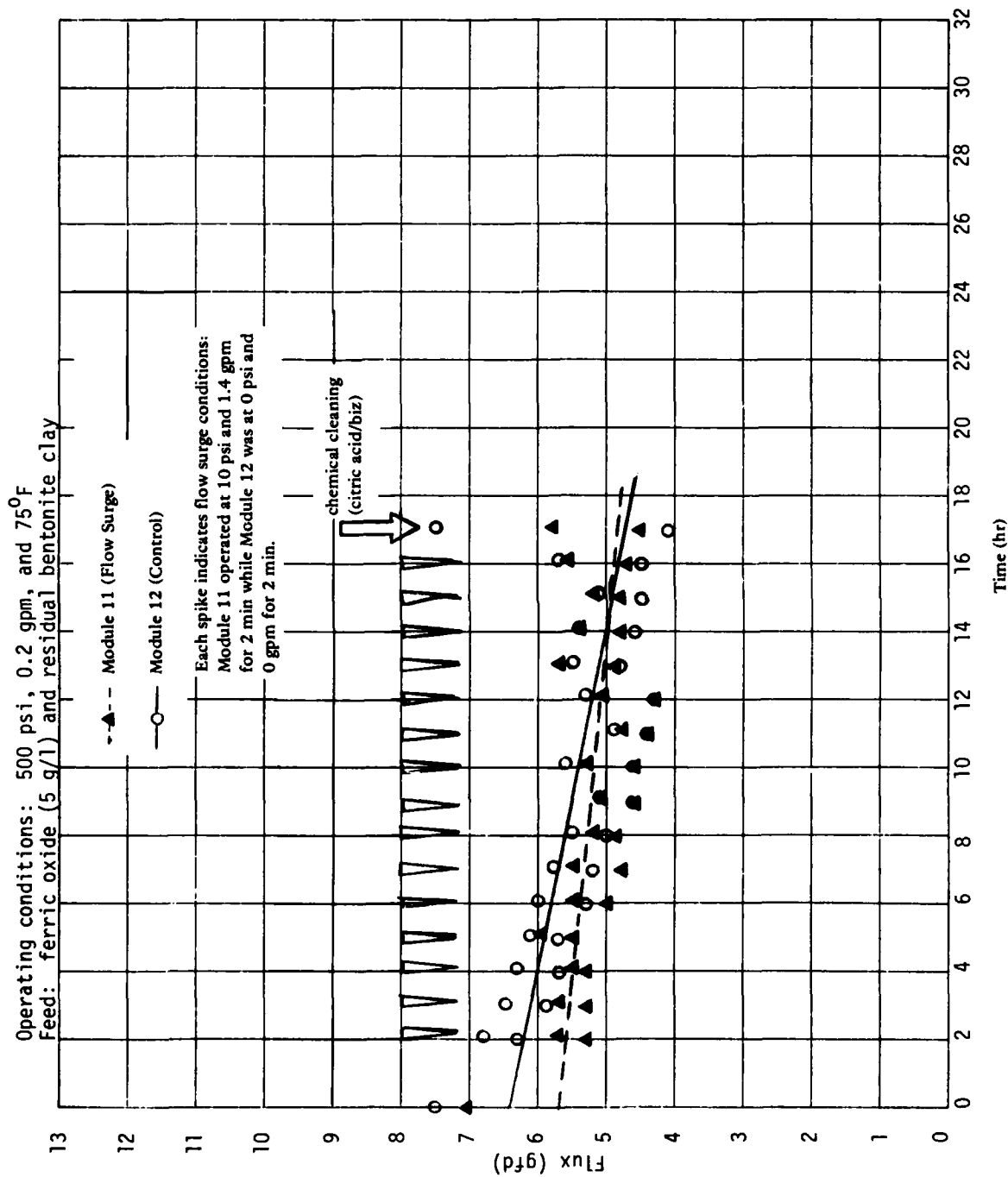
Figure 25. Frequent unidirectional flow surging.

65

Operating conditions: 500 psi, 0.2 gpm, and 75°F   BP denotes blocked permeate line.
Feed: ferric oxide (5 g/l and residual bentonite clay
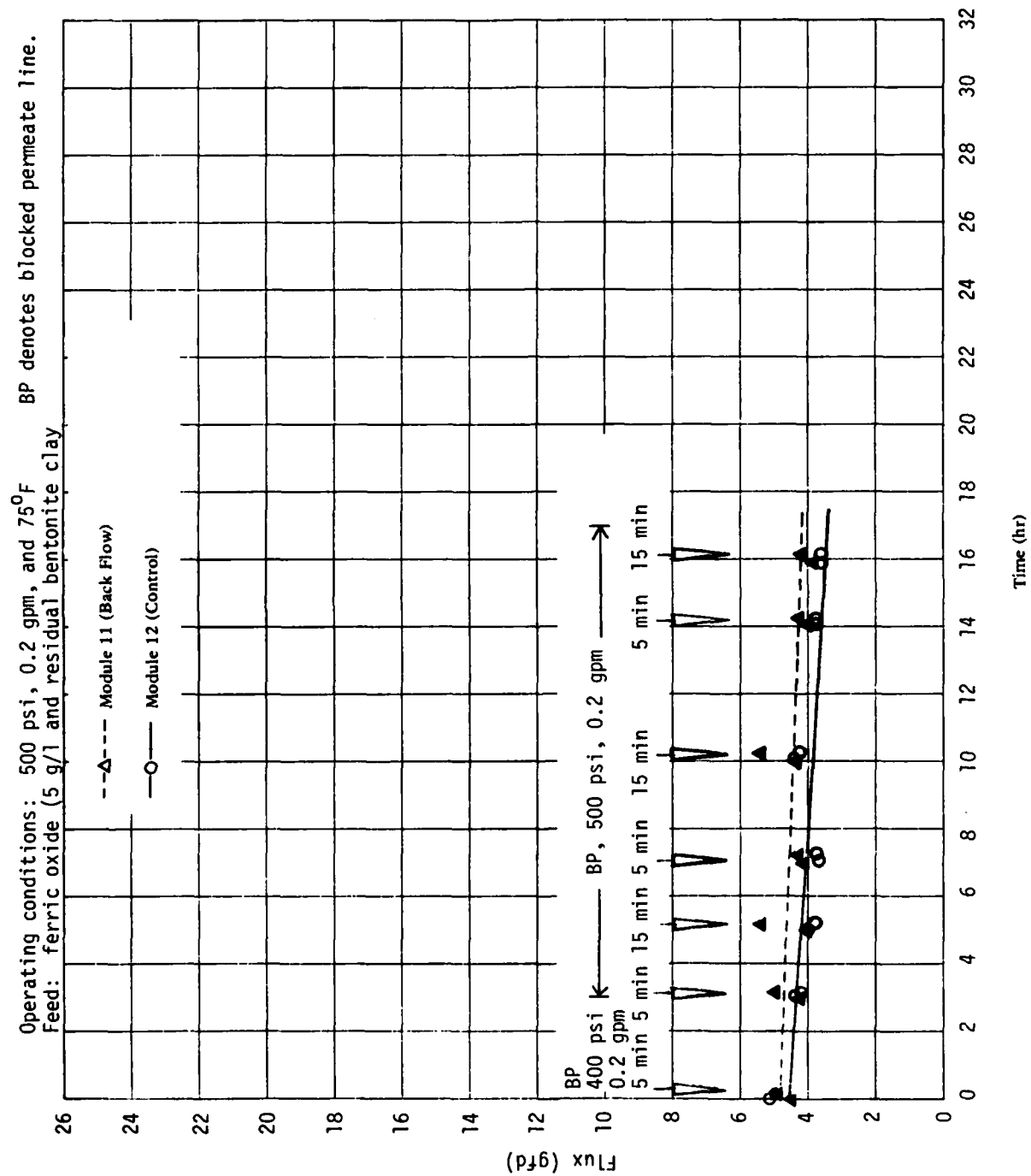
Figure 26. Blocked permeate line cleaning.
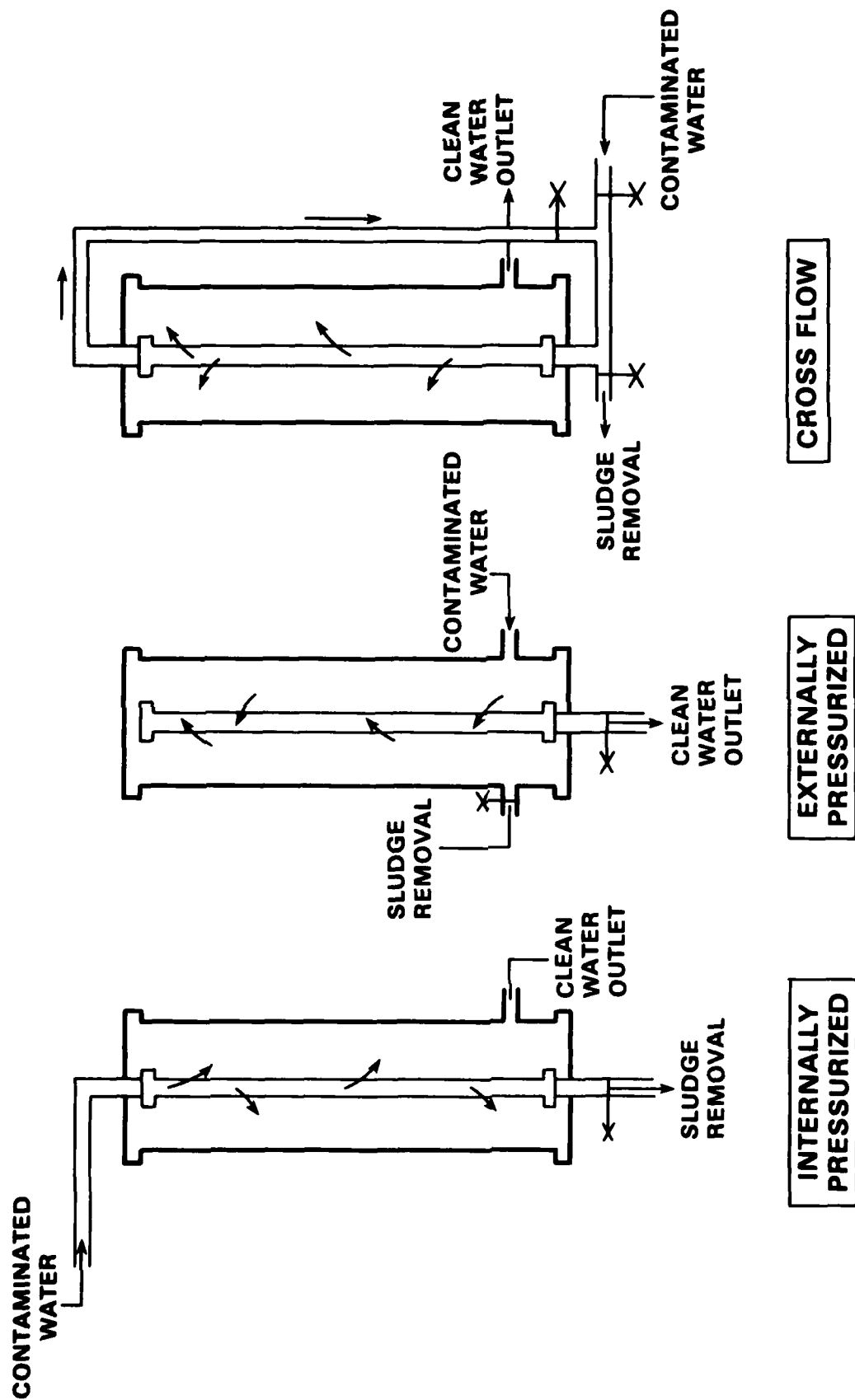
Figure 27. Operational modes of the tubular fabric filter.
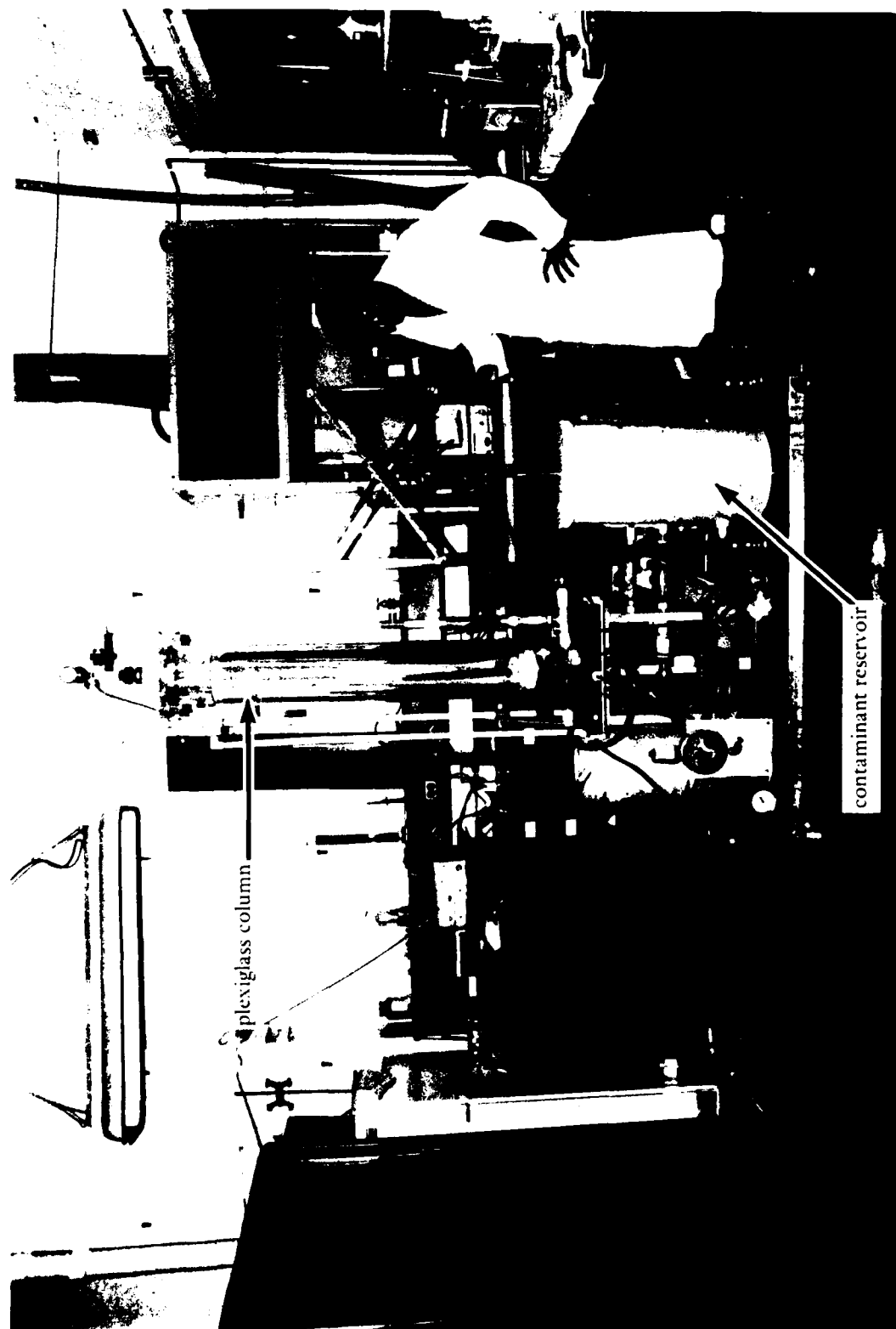
Figure 28. Front view of the TF² experimental model.

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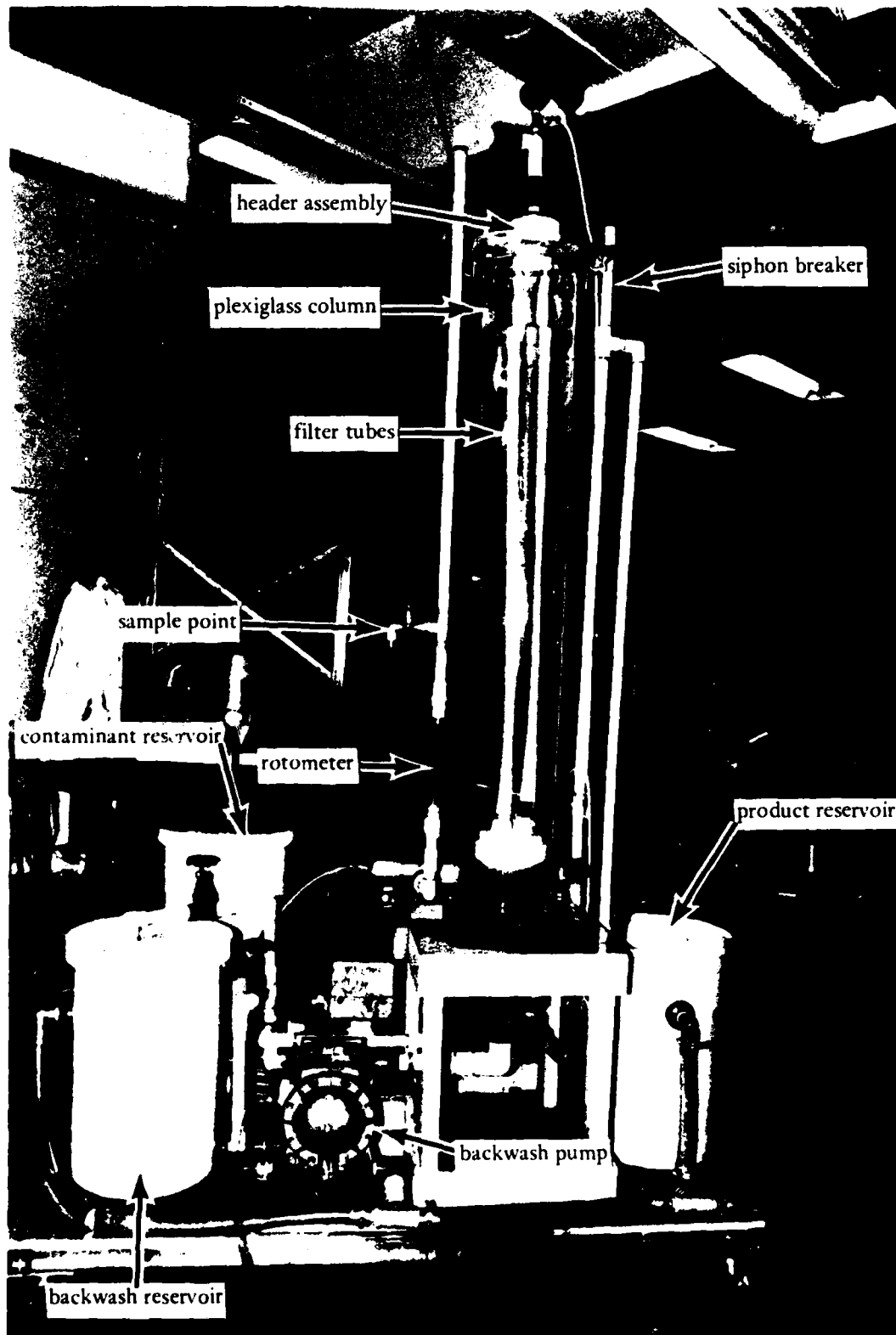
Figure 29. Back view of the TF^2 experimental model.
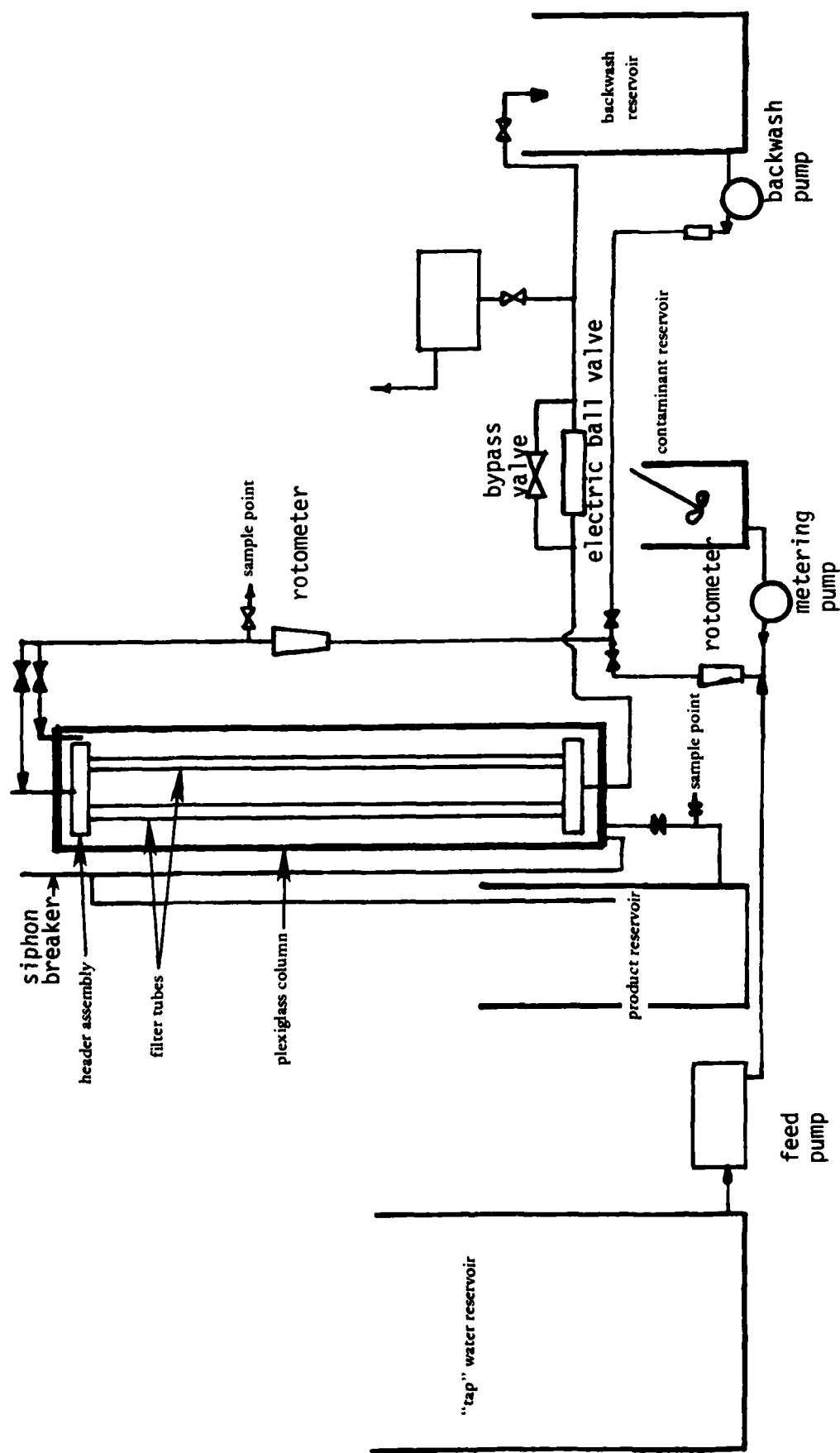
Figure 30. Schematic diagram of the TF^2 experimental model.
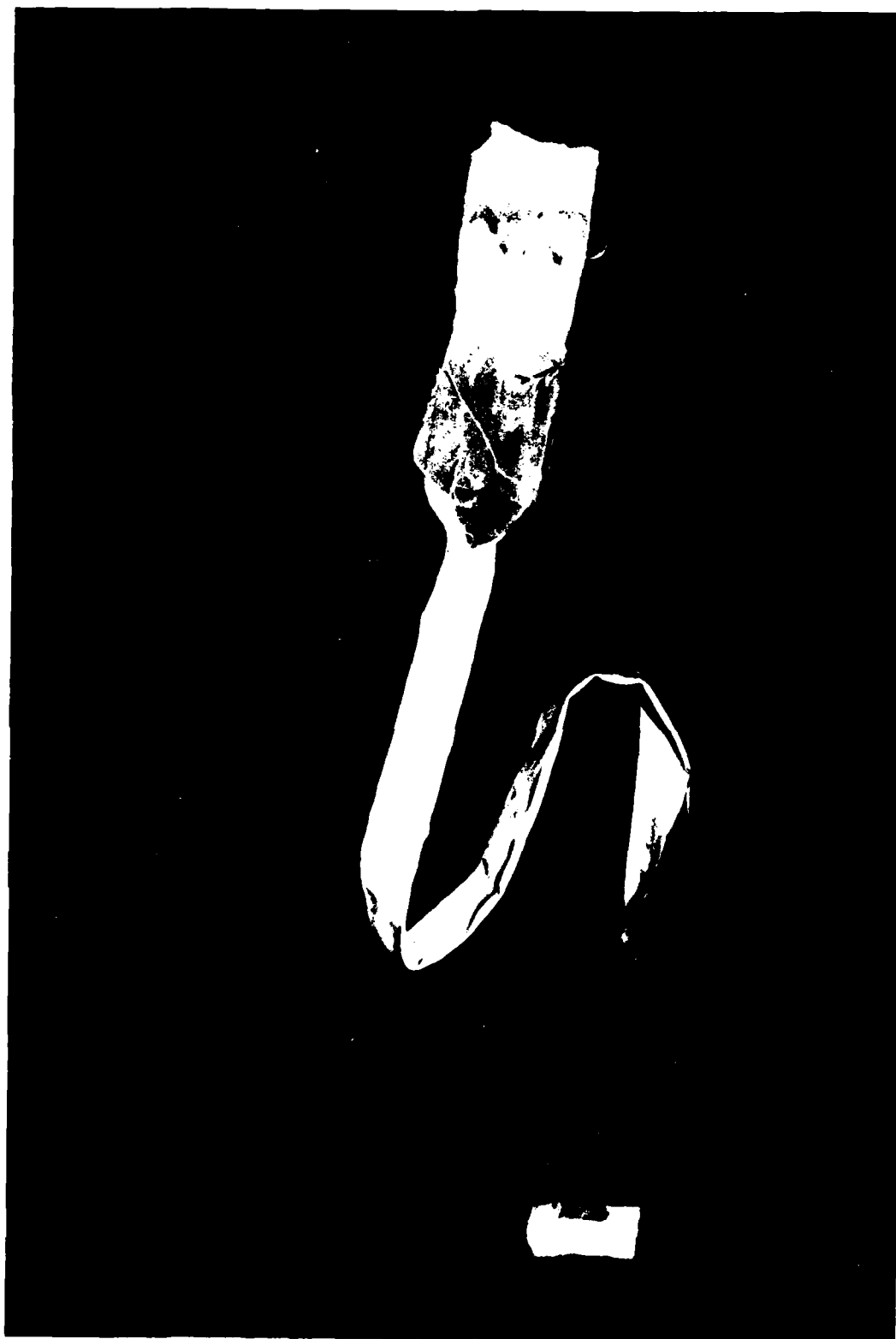
Figure 31. Fabric Type I split open to show dirt on internal fabric.
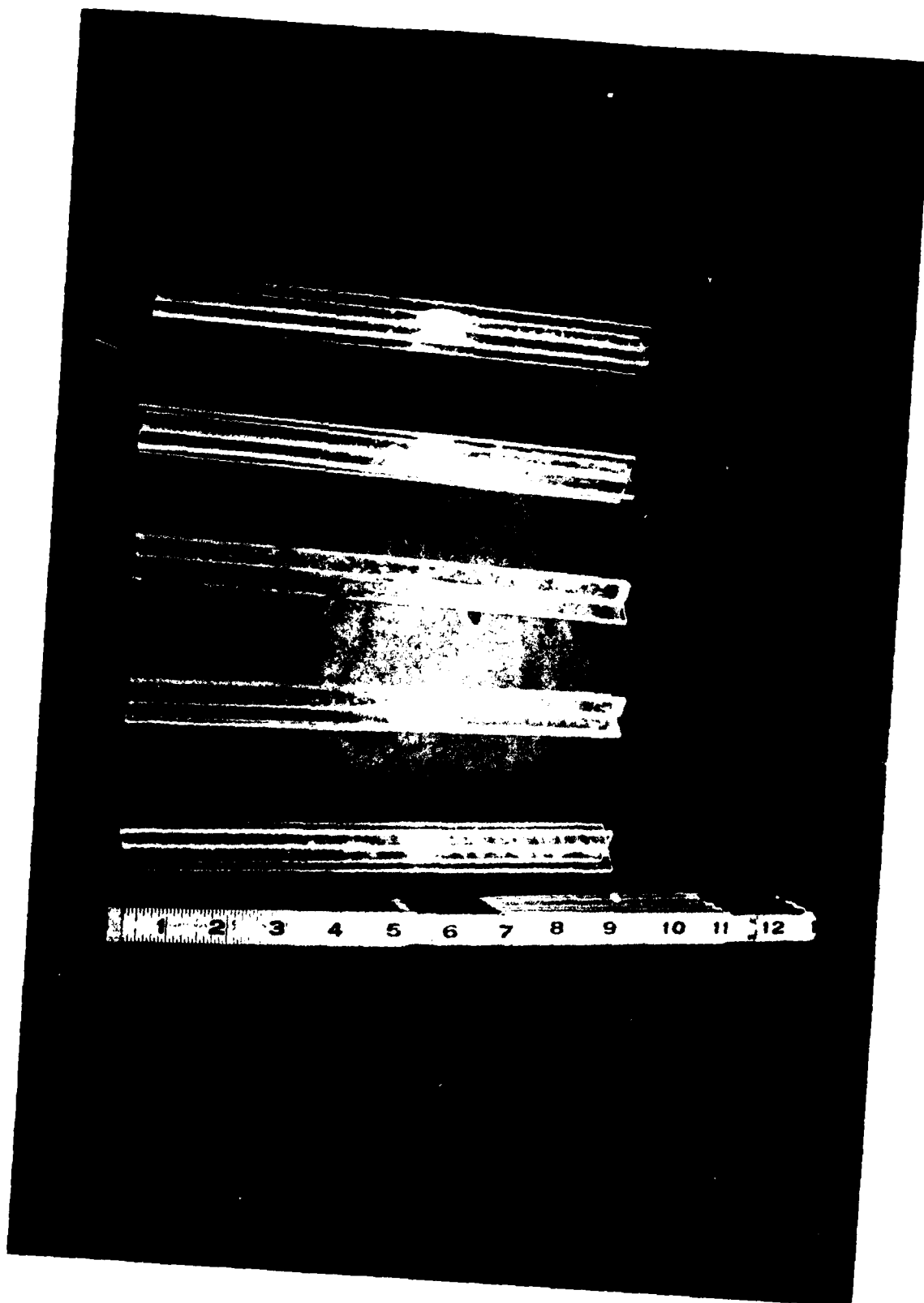
Figure 32. Supports used inside the filter tubes for reverse flow.

72
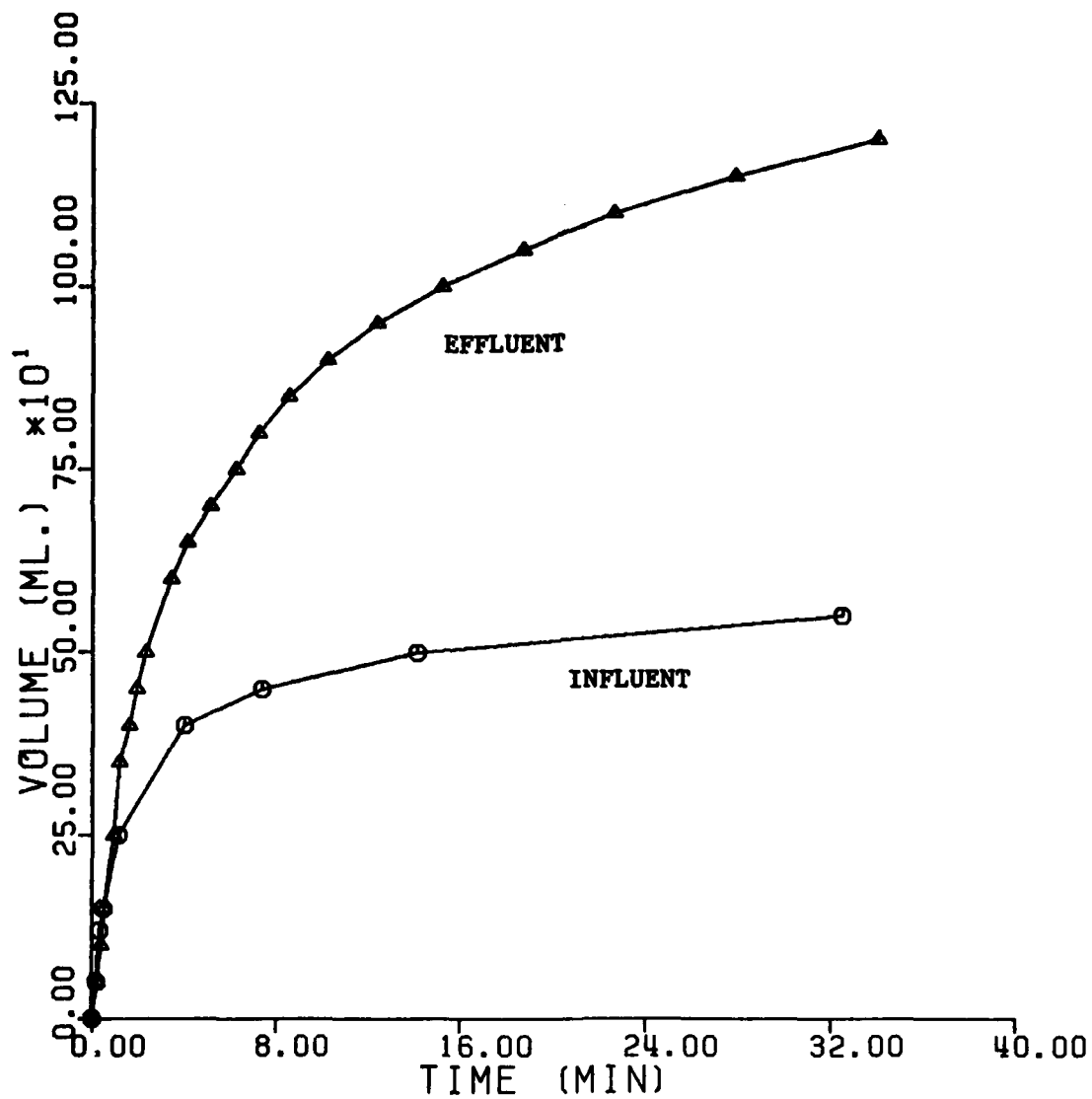
Figure 33. Flux decline tests.

73
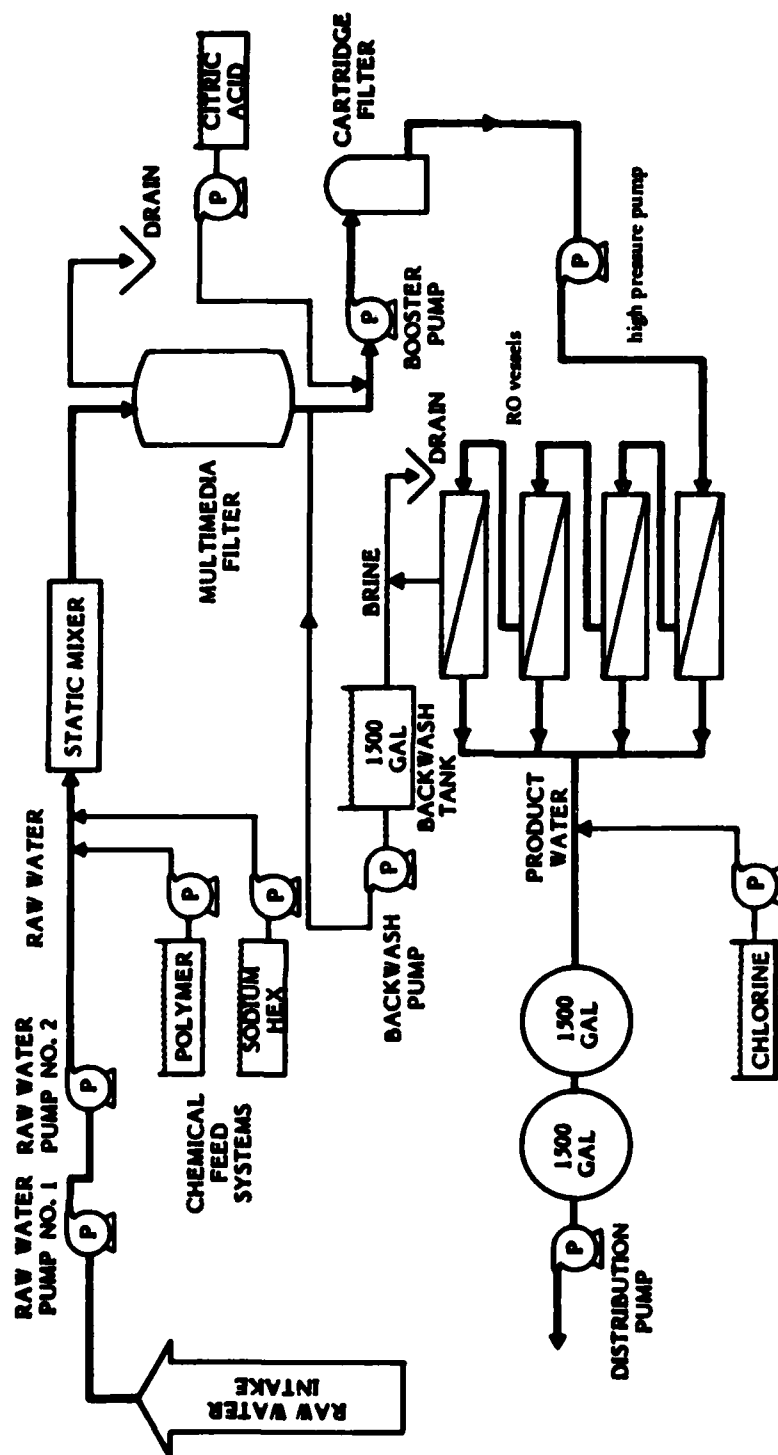
Figure 34. Process diagram for the ROWPU.

V₁, V₂, V₃, High Pressure Pump - In Present ROWPU

V₄, V₅, V₆, Added for automated testing system

P₁, P₂, Added for testing
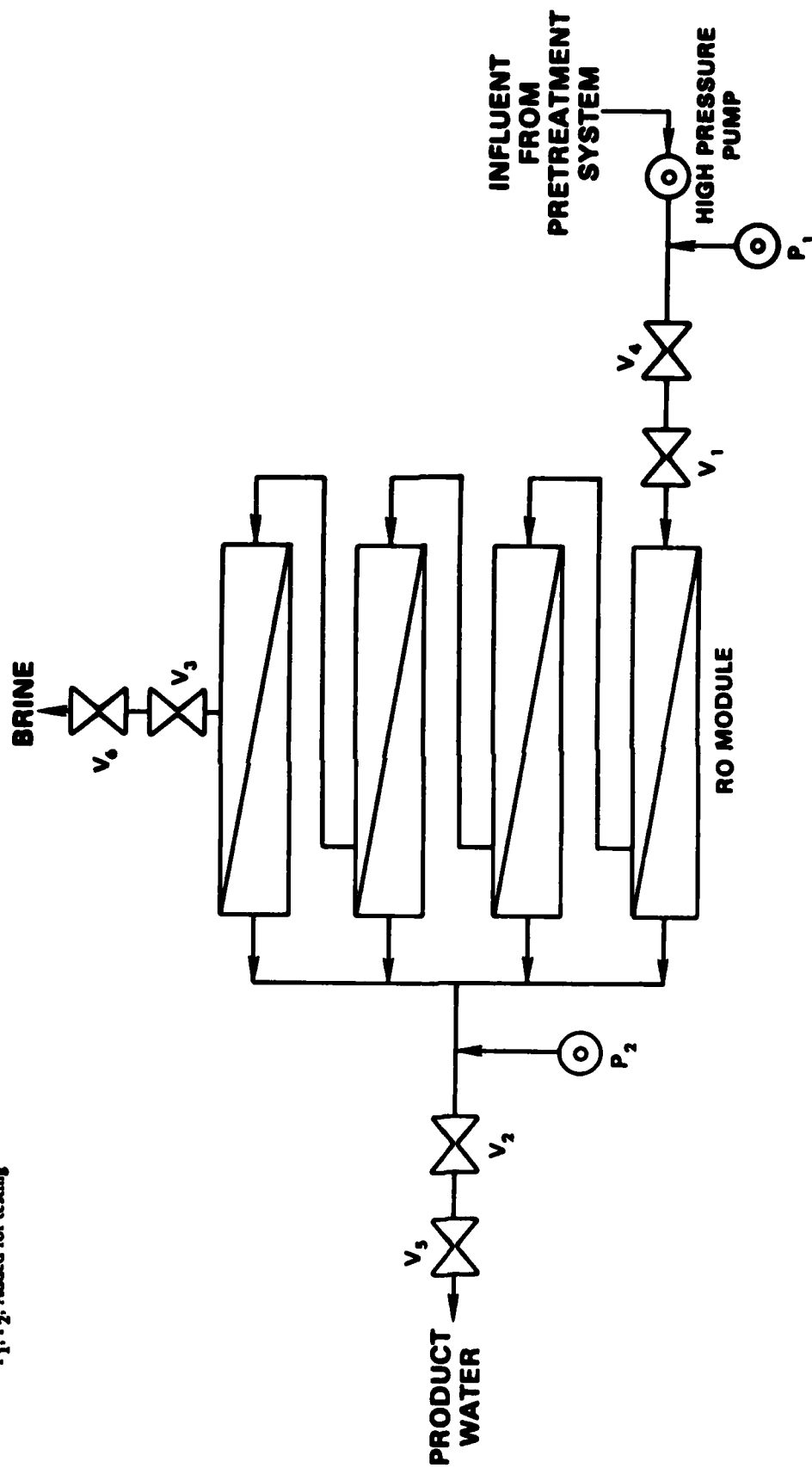
Figure 35. Proposed modification of ROWPU for flow surge cleaning evaluation.

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Appendix

**GRAPHS OF PRESSURE VERSUS TIME FOR THE SEQUENCE
OF FILTRATION/BACKWASHING EXPERIMENTS
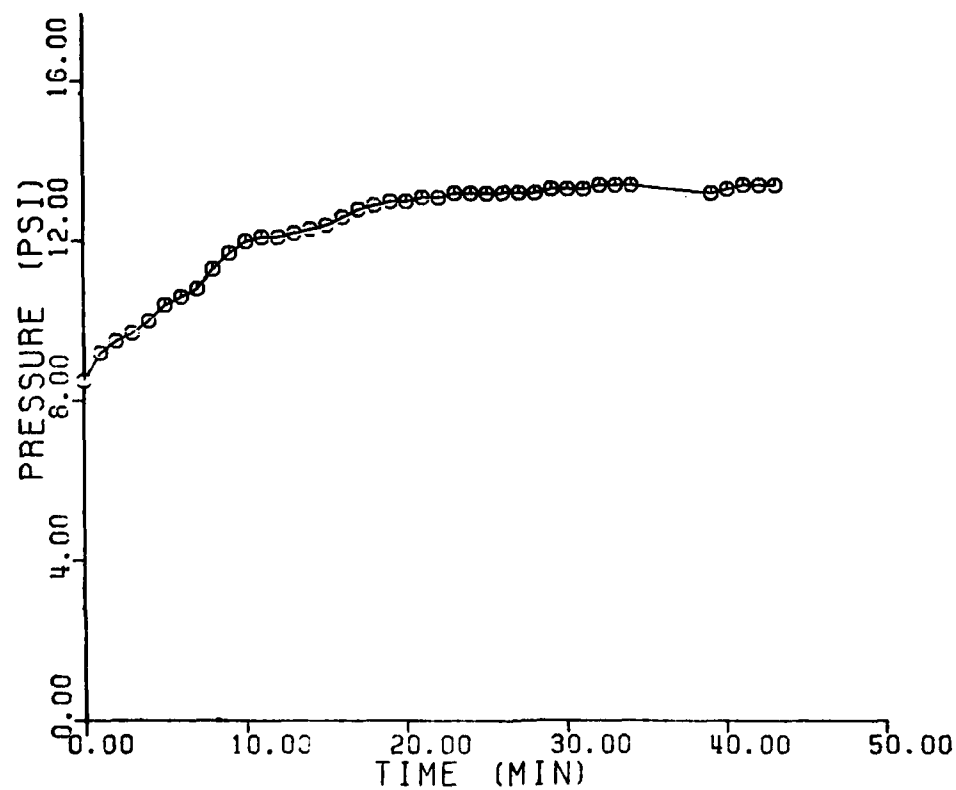SHOWN IN TABLE 15 ARE PRESENTED IN THIS APPENDIX**
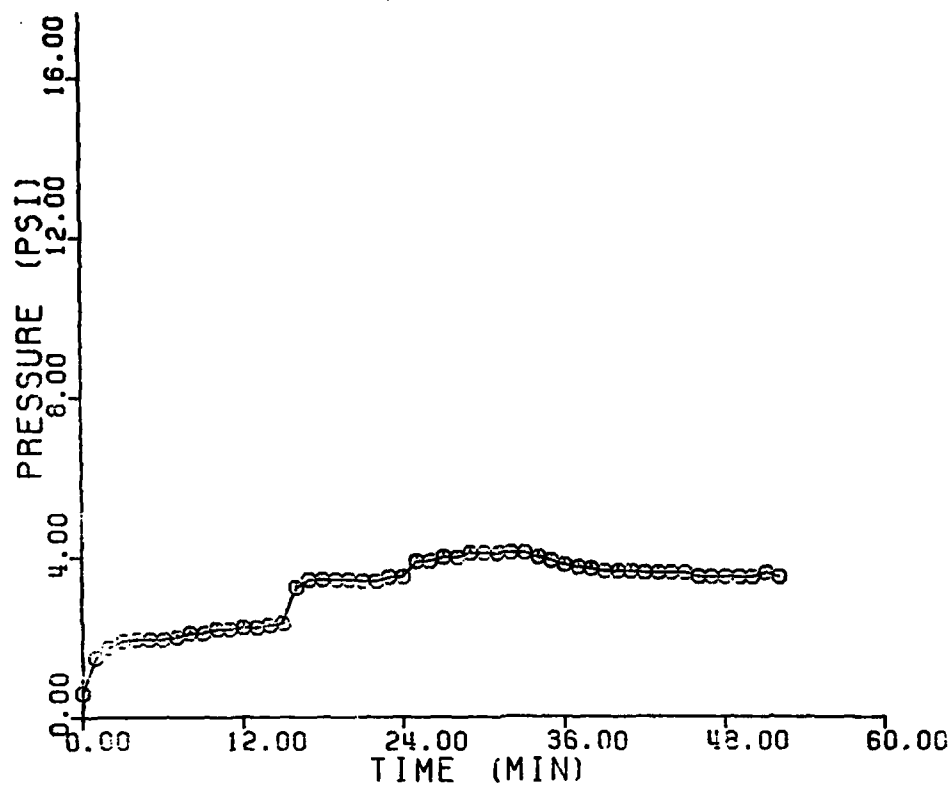
Figure 36. Pressure versus time for cross-flow operation at 1.0 gpm, Test no. 1.
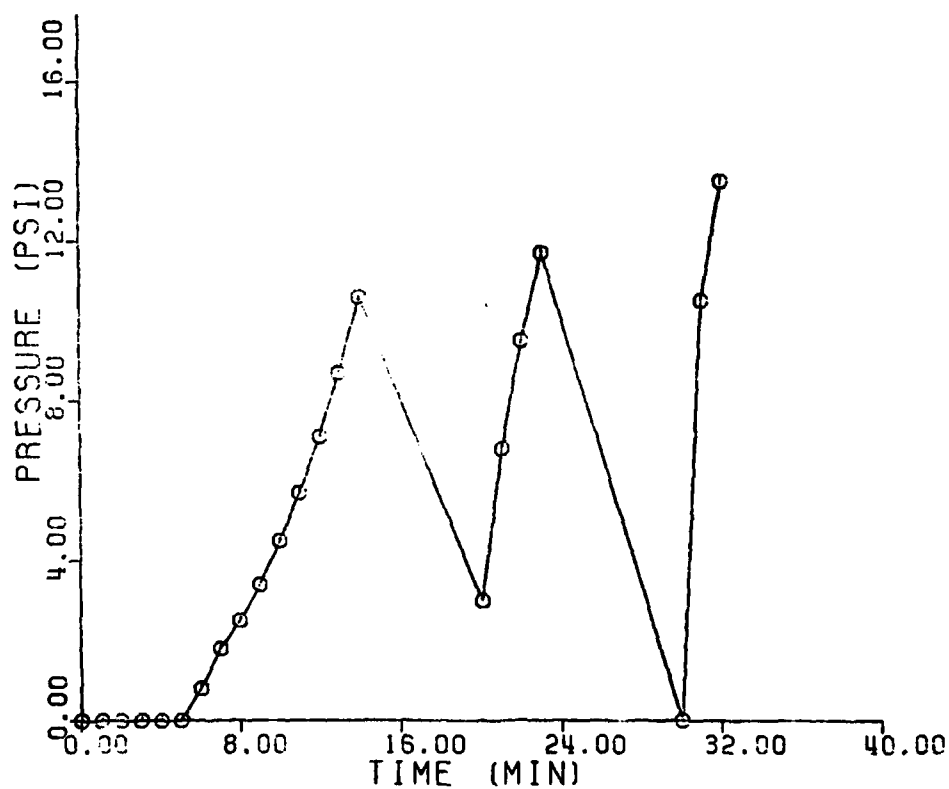
Figure 37. Pressure versus time for closed-end operation at 4.0 gpm, Test no. 2.
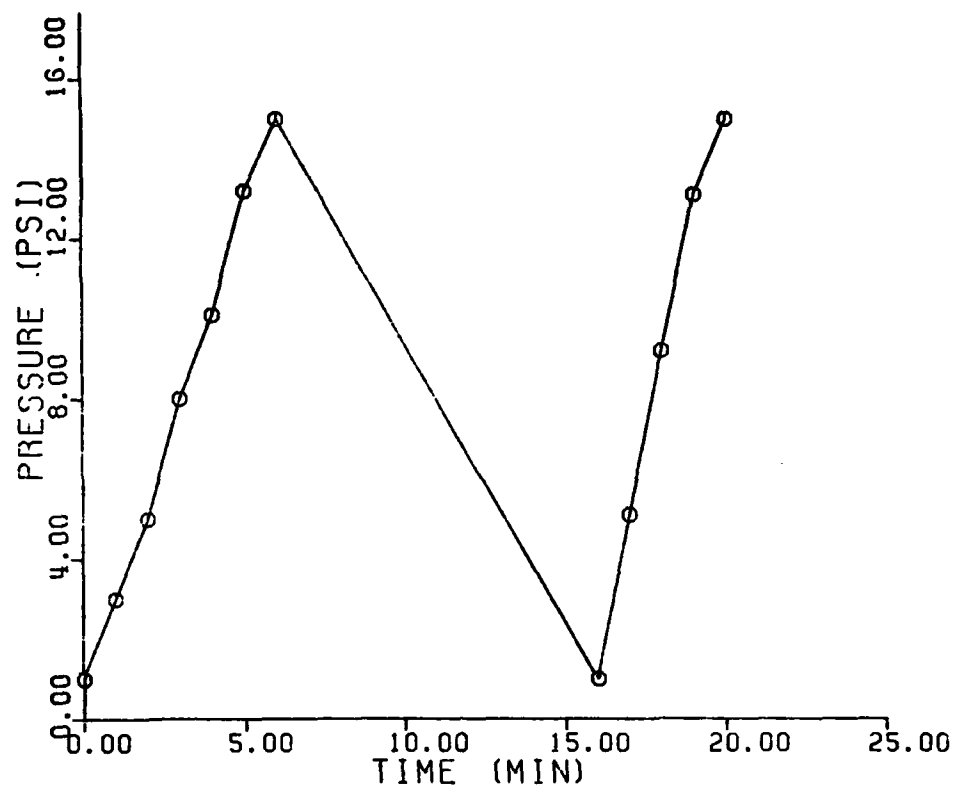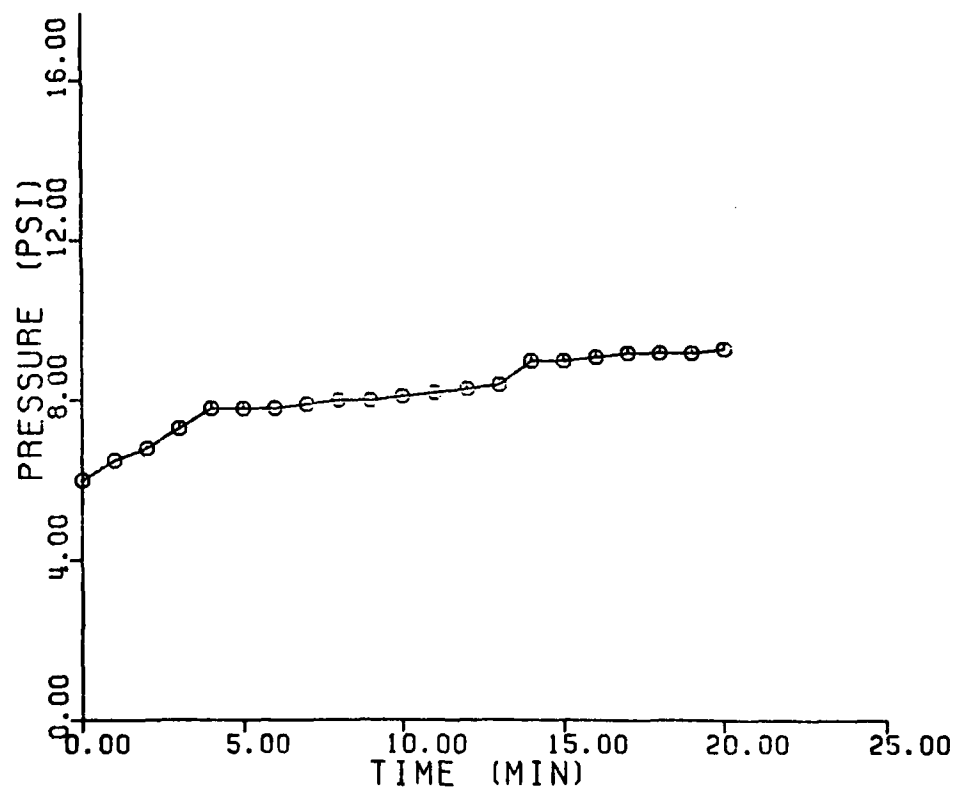
79
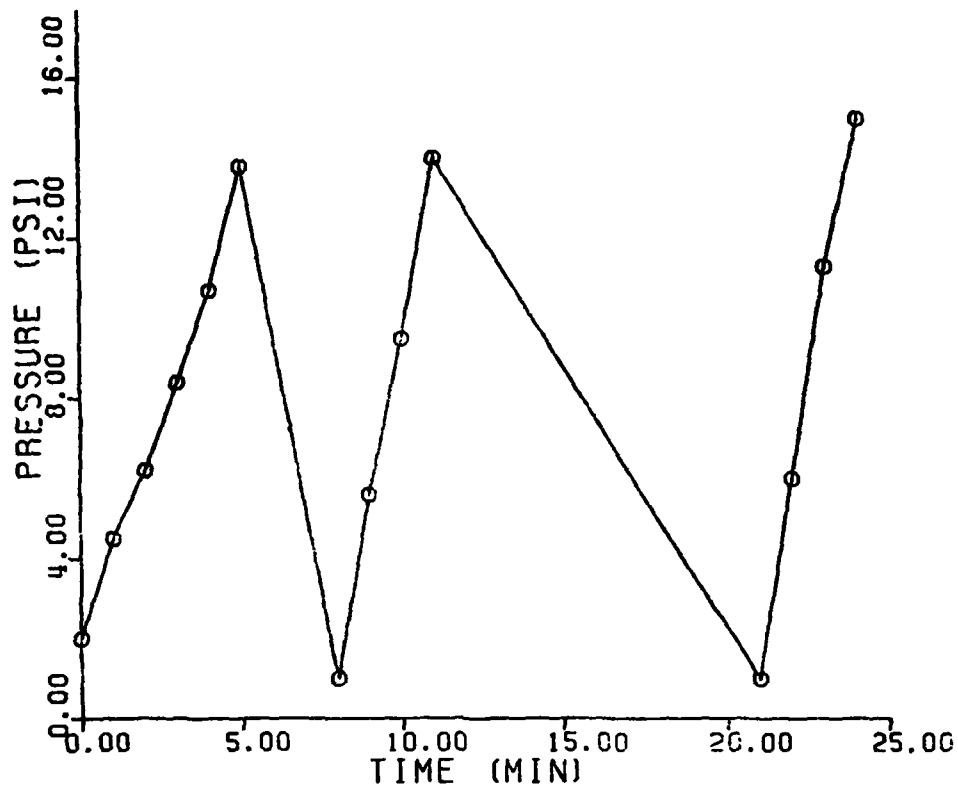
Figure 38. Pressure versus time for closed-end operation at 4.0 gpm, Test no. 3.
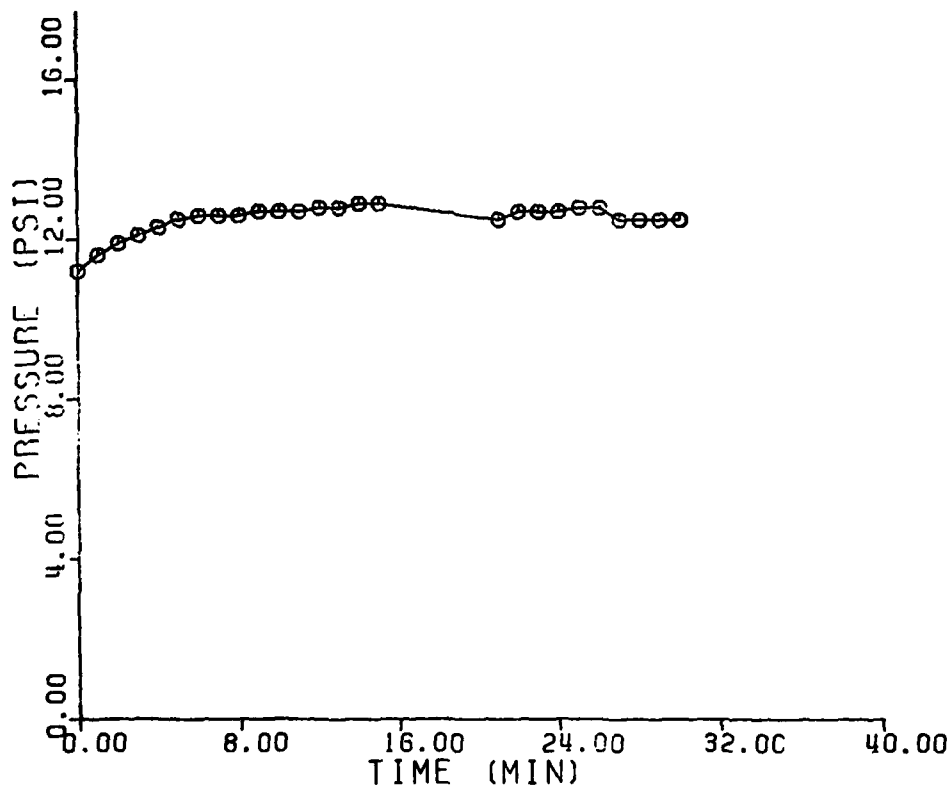
Figure 39. Pressure versus time for cross-flow operation at 4.0 gpm, Test no. 4.
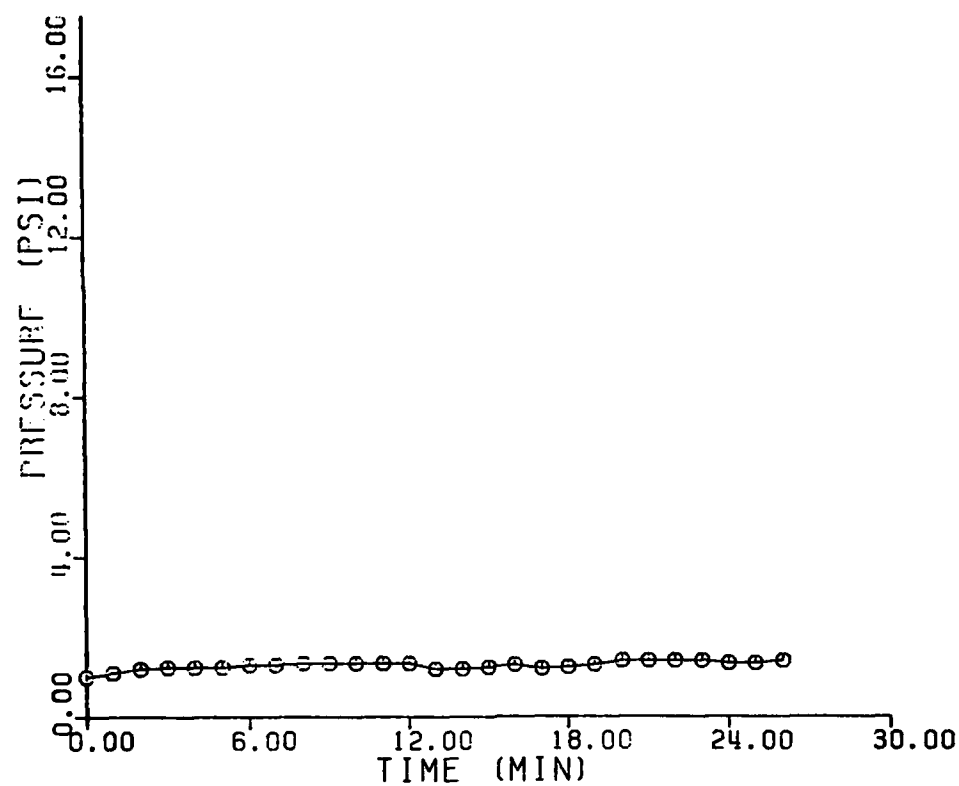
Figure 40. Pressure versus time for cross-flow operation at 1.0 gpm, Test no. 5.

Figure 41. Pressure versus time for cross-flow operation at 4.0 gpm, Test no. 6.

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Figure 42. Pressure versus time for closed-end operation at 4.0 gpm, Test no. 7.

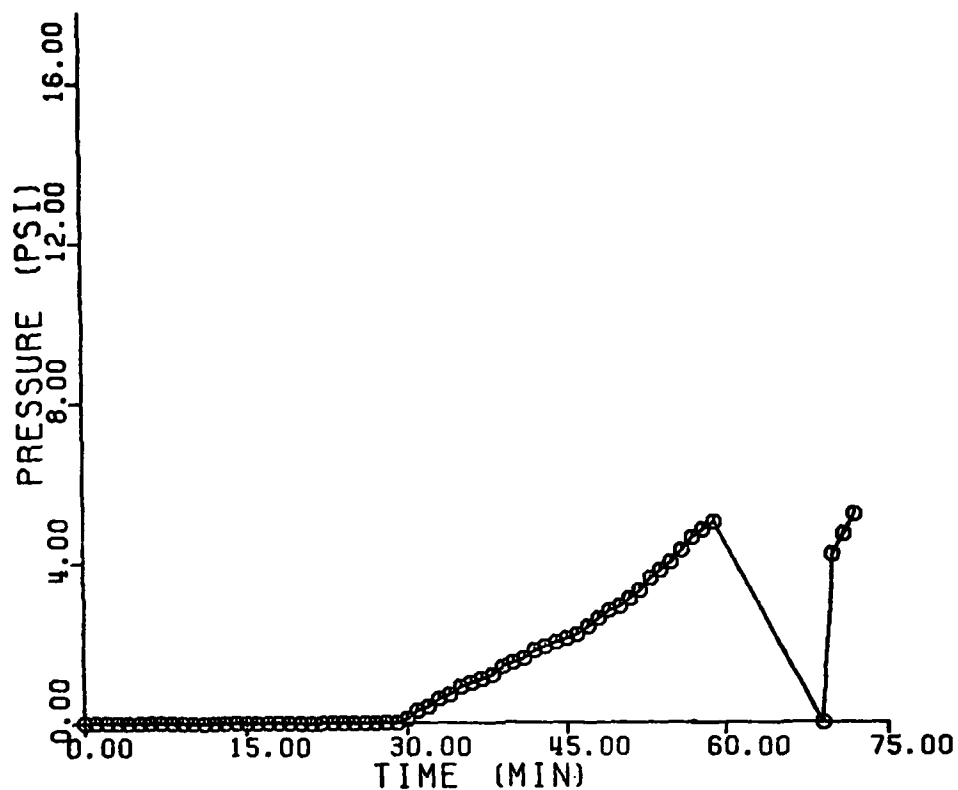Figure 43. Pressure versus time for cross-flow operation at 4.0 gpm, Test no. 8.

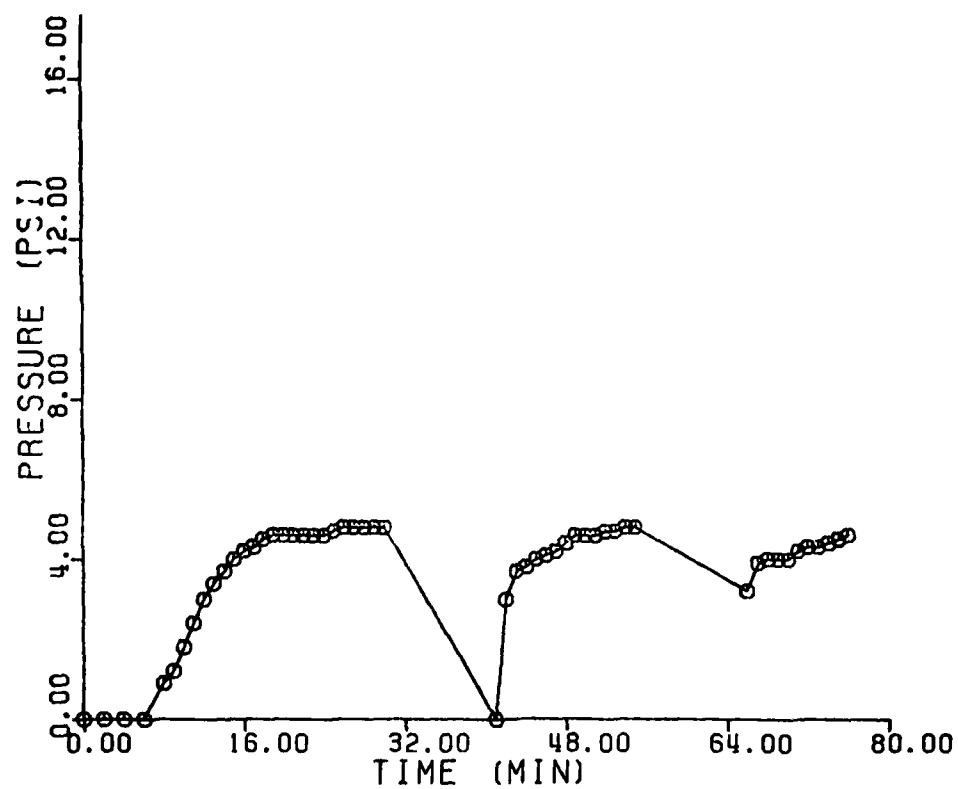Figure 44. Pressure versus time for closed-end operation at 1.0 gpm, Test no. 9.

Figure 45. Pressure versus time for closed-end operation at 1.0 gpm, Test no. 10.
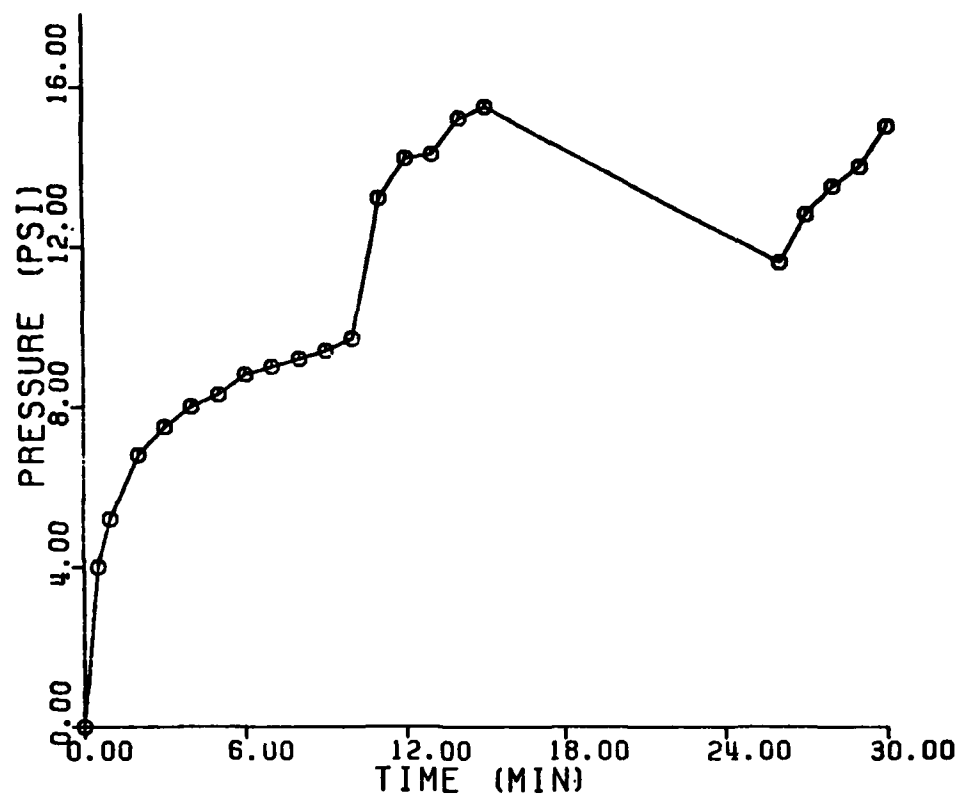
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Figure 46. Pressure versus time for closed-end operation at 1.0 gpm, Test no. 11.
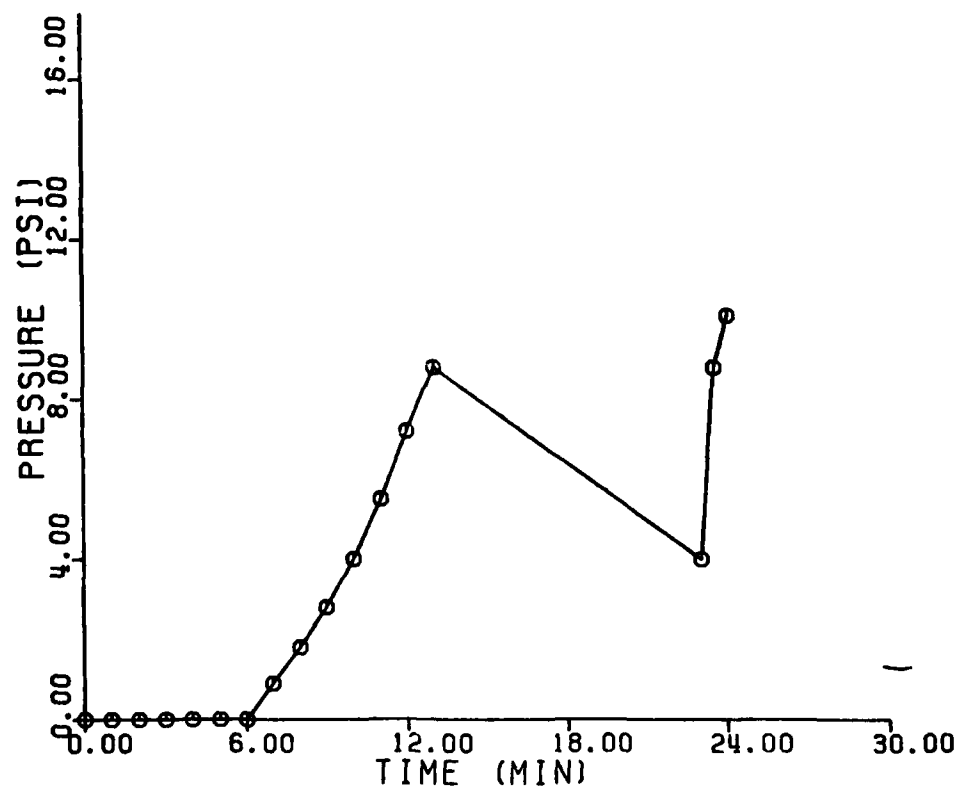

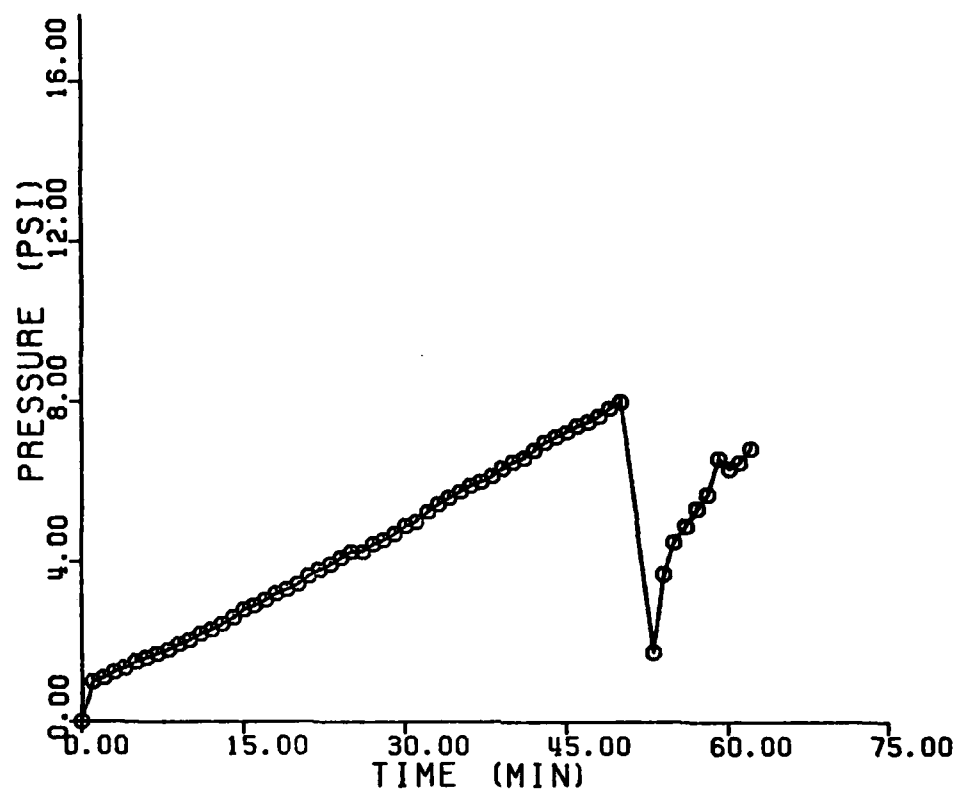Figure 47. Pressure versus time for closed-end operation at 4.0 gpm, Test no. 12.

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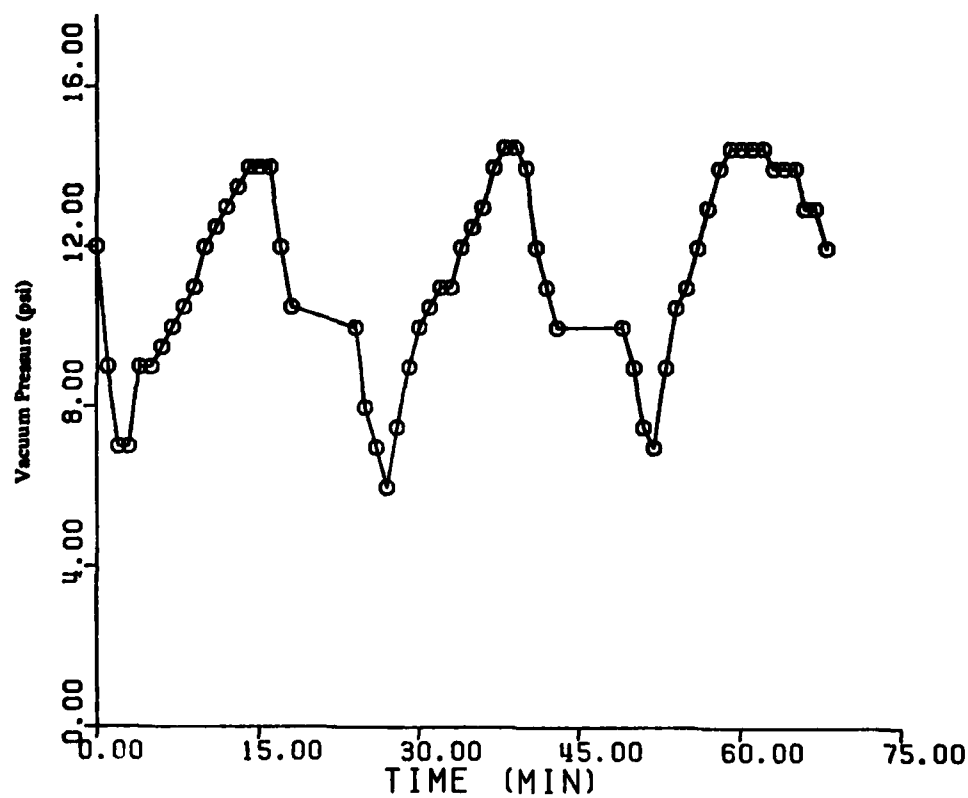Figure 48. Pressure versus time for closed-end operation at 1.0 gpm, Test no. 13.

Figure 49. Pressure versus time for reverse flow operation at 2.0 gpm, Test no. 14.

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NAVFACENGCOM - LANT DIV. Code 403, Norfolk, VA; Code 405 Civil Engr BR Norfolk VA; Eur. BR Deputy Dir, Naples Italy; RDT&ELO 102A, Norfolk, VA

NAVFACENGCOM - NORTH DIV. (Boretsky) Philadelphia, PA; CO; Code 04 Philadelphia, PA; Code 09P Philadelphia PA; Code 1028, RDT&ELO, Philadelphia PA; Code 111 Philadelphia, PA; Code 114 (A. Rhoads); ROICC, Contracts, Crane IN

NAVFACENGCOM - PAC DIV. CODE 09P PEARL HARBOR HI; Code 2011 Pearl Harbor, HI; Code 402, RDT&E, Pearl Harbor HI; Commander, Pearl Harbor, HI

NAVFACENGCOM - SOUTH DIV. Code 90, RDT&ELO, Charleston SC

NAVFACENGCOM - WEST DIV. AROICC, Contracts, Twentynine Palms CA; Code 04B San Bruno, CA; Code 114C, San Diego CA; O9P/20 San Bruno, CA; RDT&ELO Code 2011 San Bruno, CA

NAVFACENGCOM CONTRACTS AROICC, Point Mugu CA; AROICC, Quantico, VA; Dir, Eng. Div., Exmouth, Australia; Eng Div dir, Southwest Pac, Manila, PI; OICC, Southwest Pac, Manila, PI; OICC-ROICC, NAS Oceana, Virginia Beach, VA; OICC/ROICC, Balboa Panama Canal; ROICC AF Guam; ROICC, Keflavik, Iceland; ROICC, NAS, Corpus Christi, TX; ROICC, Pacific, San Bruno CA; ROICC-OICC-SPA, Norfolk, VA

NAVFORCARIB Commander (N42), Puerto Rico

NAVMAG PWD - Engr Div, Guam

NAVOCEANO Library Bay St. Louis, MS

NAVORDSTA PWO, Louisville KY

NAVPETOFF Code 30, Alexandria VA

NAVPETRES Director, Washington DC

NAVPGSCOL E. Thornton, Monterey CA

NAVPHIBASE CO, ACB 2 Norfolk, VA; Code S3T, Norfolk VA; SCE Coronado, SD,CA

NAVRADRECFAC PWO, Kami Seya Japan

NAVREGMEDCEN Code 29, Env. Health Serv, (Al Bryson) San Diego, CA; SCE, Newport, RI

NAVREGMEDCEN PWO, Okinawa, Japan

NAVREGMEDCEN SCE; SCE San Diego, CA; SCE, Camp Pendleton CA; SCE, Oakland CA

NAVREGMEDCEN SCE, Yokosuka, Japan

NAVREGMEDCLINIC A. Watanabe, Pearl Harbor, HI

NAVSCOLCECOFF C35 Port Hueneme, CA; CO, Code C44A Port Hueneme, CA

NAVSCSOL PWO, Athens GA

NAVSEASYSCOM SEA 04E (L Kess) Washington, DC

NAVSECGRUACT Facil. Off., Galeta Is. Panama Canal; PWO, Adak AK; PWO, Edzell Scotland; PWO, Puerto Rico

NAVSHIPYD Bremerton, WA (Carr Inlet Acoustic Range); Code 202.5 (Library) Puget Sound, Bremerton WA; Code 380, Portsmouth, VA; Code 400, Puget Sound; Code 410, Mare Is., Vallejo CA; Code 440 Portsmouth NH; Code 440, Norfolk; Code 440, Puget Sound, Bremerton WA; L.D. Vivian; Library, Portsmouth NH; PW Dept, Long Beach, CA; PWD (Code 420) Dir Portsmouth, VA; PWD (Code 450-HD) Portsmouth, VA; PWO, Bremerton, WA; PWO, Mare Is.; PWO, Puget Sound; SCE, Pearl Harbor HI; Tech Library, Vallejo, CA

NAVSTA CO Roosevelt Roads P.R. Puerto Rico; CO, Brooklyn NY; Code 4, 12 Marine Corps Dist, Treasure Is., San Francisco CA; Dir Engr Div, PWD, Mayport FL; Engr. Dir., Rota Spain; Long Beach, CA; Maint. Cont. Div., Guantanamo Bay Cuba; Maint. Div. Dir/Code 531, Rodman Panama Canal; PWD - Engr Dept, Adak, AK; PWD - Engr Div, Midway Is.; PWO, Keflavik Iceland; PWO, Mayport FL; SCE, Guam; SCE, Subic Bay, R.P.; Security Offr, San Francisco, CA

NAVSUBASE SCE, Pearl Harbor HI

NAVSUPPFAC PWD - Maint. Control Div, Thurmont, MD

NAVTECHTRACEN SCE, Pensacola FL

NAVWPNCEN Code 2636 China Lake; Code 3803 China Lake, CA; PWO (Code 266) China Lake, CA

NAVWPNSTA Code 092, Colts Neck NJ; Maint. Control Dir., Yorktown VA

NAVWPNSTA PW Office Yorktown, VA

NAVWPNSTA PWD - Maint Control Div, Charleston, SC; PWD - Maint. Control Div., Concord, CA; PWD - Supr Gen Engr, Seal Beach, CA; PWO, Charleston, SC; PWO, Seal Beach CA

NAVWPNSUPPCEN Code 09 Crane IN

NCTC Const. Elec. School, Port Hueneme, CA

NCBC Code 10 Davisville, RI; Code 15, Port Hueneme CA; Code 155, Port Hueneme CA; Code 156, Port Hueneme, CA; Code 25111 Port Hueneme, CA; Code 400, Gulfport MS; Code 430 (PW Engrng) Gulfport, MS; NEESA Code 252 (P Winters) Port Hueneme, CA; PWO (Code 80) Port Hueneme, CA; PWO, Gulfport, MS

NCR 20, Code R70; 20, Commander

NMCB 74, CO; FIVE, Operations Dept; Forty, CO; THREE, Operations Off.

NOAA Library Rockville, MD

NORDA Code 410 Bay St. Louis, MS; Code 440 (Ocean Rsch Off) Bay St. Louis MS

NSC Code 54.1 Norfolk, VA

NSD SCE, Subic Bay, R.P.

NSWSES Code 0150 Port Hueneme, CA

NTC OICC, CBU-401, Great Lakes IL

NUCLEAR REGULATORY COMMISSION T.C. Johnson, Washington, DC

NUSC Code 131 New London, CT; Code EA123 (R.S. Munn), New London CT; Code SB 331 (Brown), Newport RI

ONR Code 700F Arlington VA

PHIBCB 1 P&E, San Diego, CA; 1, CO San Diego, CA; 1, CSWC D Wellington, San Diego, CA

PMTC Pat. Counsel, Point Mugu CA

PWC CO Norfolk, VA; CO, (Code 10), Oakland, CA; CO, Great Lakes IL; CO, Pearl Harbor HI; Code 10, Great Lakes, IL; Code 105 Oakland, CA; Code 120, Oakland CA; Code 120C, (Library) San Diego, CA; Code 128, Guam; Code 154, Great Lakes, IL; Code 200, Great Lakes IL; Code 30V, Norfolk, VA; Code 400, Great Lakes, IL; Code 400, Oakland, CA; Code 400, Pearl Harbor, HI; Code 400, San Diego, CA; Code 420, Oakland, CA; Code 424, Norfolk, VA; Code 505A Oakland, CA; Code 600, Great Lakes, IL; Code 610, San Diego Ca; Code 700, Great Lakes, IL; Code 700, San Diego, CA; Util Dept (R Pascua) Pearl Harbor, HI; Utilities Officer, Guam

SUPANX PWO, Williamsburg VA

TVA Solar Group, Arnold, Knoxville, TN

US DEPT OF HEALTH, ED., & WELFARE Food & Drug Admin, (A. Story), Dauphin Is. AL

US GEOLOGICAL SURVEY Off. Marine Geology, Piteleki, Reston VA

US NAVAL FORCES Korea (ENJ-P&O)

USAF REGIONAL HOSPITAL Fairchild AFB, WA

USCG (Smith), Washington, DC

USDA Forest Service Reg 3 (R. Brown) Albuquerque, NM; Forest Service, Bowers, Atlanta, GA; Forest Service, San Dimas, CA

USNA Civil Engr Dept (R. Erchyl) Annapolis MD; ENGRNG Div. PWD, Annapolis MD; Energy-Environ Study Grp, Annapolis, MD; Environ. Prot. R&D Prog. (J. Williams), Annapolis MD; NAVSYSENGR Dept. Annapolis, MD; PWO Annapolis MD

BROOKHAVEN NATL LAB M. Steinberg, Upton NY

GEORGIA INSTITUTE OF TECHNOLOGY (LT R. Johnson) Atlanta, GA

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